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BLAST/FIRE INTERACTIONS

Program Formulation

October 1978

LEVEL II

Final Report

By: Stanley B. Martin
Raymond S. Alger

Prepared for:

DEFENSE CIVIL PREPAREDNESS AGENCY
Washington, D.C. 20301
Attn: David W. Bensen, COTR

Contract No. DCPAN1-78-C-0225
DCPA Work Unit 2563D

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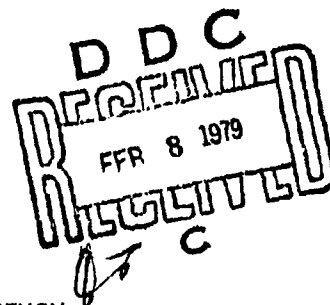
SRI International
333 Ravenswood Avenue
Menlo Park, California 94025
Cable: SRI INTL MNP
TWX: 910-373-1246



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Approved:



Paul J. Jorgensen, Vice President
Physical and Life Sciences

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ABSTRACT

This report is based on material generated during a DCPA-sponsored conference on blast-fire interactions held May 21-24, 1978 at Asilomar, California. The conference was convened to allow a selected group of authorities on fire, air blast, structural response, and related technologies to rethink the blast-fire effects of nuclear explosions on urban areas, to identify technical deficiencies in the current state of the predictive modeling art, and to plan a feasible research program to be accomplished within a reasonable time and budget.

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SUMMARY

Fire from a nuclear-weapons attack is a direct threat to the population of the United States and an indirect, long-term threat to national survival because fire can destroy the shelter, sustaining resources, and industrial machinery essential to economic recovery. Unresolved questions about interactions between blast effects and fire effects preclude any reliable estimates of the incendiary outcome of a nuclear attack on the United States. As such, these uncertainties are a major obstacle to defense planning and interfere with national security policymaking at the highest levels.

To rectify the technical deficiencies underlying the lack of predictability of the incendiary outcome of nuclear attack on the United States and to formulate a well-directed program of research, the Defense Civil Preparedness Agency contracted with SRI International in early 1978 to convene a conference of authorities on fire, air blast, structural response, and related technologies. This report covers the proceedings of that conference and its accomplishments.

The conferees identified the technical deficiencies that prevent or inhibit the development of a theoretical or analytical basis for predicting fire effects under the uncertainties introduced by interaction with air-blast waves and blast effects. Recognizing the inherent uncertainties concerning any future nuclear event, and constrained to a planning philosophy that requires the level of technical understanding to be consistent with practical utility and commensurate with the level of perceived threat, the conferees developed a logical, analytical framework for structuring and performing a research program to either eliminate technical deficiencies or reduce to an acceptable level the contribution these deficiencies add to the uncertainties in damage prediction. Recommendations were made for early attention to specific deficiencies that are readily distinguished as key issues that prevent the development of credible fire/blast models. Beyond this, most program elements could be seen in outline only, although the conferees unanimously held that analytical modeling of blast-fire interactions was not only the goal of the program, but a necessary adjunct, through sensitivity analysis, of program planning and review.

This report describes, in some detail, the first two years (fiscal years 1979 and 1980) of an optimally funded program of 5-yr duration. The technical objective of the program was to produce an analytical method for reliably predicting fire behavior and incendiary-damage production. Three levels of modeling detail were seen as the minimum requirement:

- ° A general urban fire-distribution/spread model for areas of light-to-moderate building damage.
- ° A "hole-in-the-doughnut" model, applicable to areas of heavy damage.
- ° A specific-resource vulnerability model, applicable to a critical resource threatened by fire exposure.

Choice and/or development of the necessary analytical methodology is a first order of business. Unfortunately, little progress can be made until the basic blast/fire interactions are understood. This, in turn, necessitates experimental investigations of the causal factors and concepts, and determinations of input data and empiricisms. Therefore, a strong experimental program is recommended to support and interactively complement the theoretical and analytical developments.

The FY79 program, estimated to cost \$920K, initiates development of blast/fire predictive modeling complemented by analysis of dynamic structural response and debris distribution calculations for single structures and a renewed attempt to estimate secondary fire incidence from retrospective, historical data on earthquakes, wind storms, and explosions. Experimental tasks include drag-lift experiments to complement debris translation calculations and shocktube studies of the physics of interactions of blast waves with burning objects of idealized geometry and composition. These experiments would be coordinated with the development of a dynamic-flow, boundary-layer theory for shock/fire interaction.

The FY1980 program would see a substantially increased level of activity, estimated to cost about \$1.3 million. Much of the work initiated in FY79 would be continued; verification experiments in connection with Misty Castle high-explosive tests are also suggested. Structural responses and debris distribution calculations would attempt to treat the more practical situations found in urban complexes. The development of the predictive blast/fire analytical models would parallel large and small scale experiments. If sensitivity studies, initiated in FY79, show the uncertainties to be important, the doubtful ignition thresholds for large areas of mixed fuels, especially the question of whether transient ignition is or is not important, would be reliably established through experiment.

This program is expected to culminate with one or more full-scale simulations of urban/industrial complexes subjected to the combined blast and fire effects of a nuclear explosion, possibly involving a HE test series dedicated to resolution of blast/fire problems.

A program of this scope, and relatively short duration, requires strong, consistently applied monitoring and coordination to ensure that the obtainable goals are significant, to maintain a level of performance that is consistent with need, and to synchronize complementary or dependent elements. These requirements point to the need for DCPA to

designate a lead laboratory to conduct some key across-the-board elements of the research and to direct and coordinate the variety of complimentary tasks done by contractors and other contributors.

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I INTRODUCTION

Fire has long been the single most destructive agent in time of war, and it has figured significantly in many natural disasters. In warfare, fire's preeminent role as a destroyer of man and his works appears undiminished by the replacement of conventional with nuclear weapons. Rather, the intense pulse of thermal radiation emitted by the fireball of a nuclear explosion can light more fires than the heaviest fire-bomb raids of World War II. One large nuclear weapon might cover much of a thousand-square-mile area with fires.

Fire from a nuclear-weapon attack threatens that part of the population that might escape death or injury from blast and prompt radiation effects and that might be suitably sheltered from radioactive fallout and residual radiation. Fire also threatens national viability and economic recovery because it can destroy not only the structural part of the urban environment that survives blast effects but also the heavy equipment and other industrial machinery essential to productivity, resupply, and reconstruction.

Current U.S. planning, based on assumptions of national resolve and effective preparedness actions in a period of crisis preceding attack, contemplates two actions:

- The relocation of high-risk elements of the population to minimize its exposure to direct effects.
- Expedient implementation of countermeasures to protect the population (mainly from fallout) and the critical utilities, industries, and resources (mainly from blast).

Much of the heavy industrial machinery in the United States can survive the blast effects of any foreseeable attack so that, following a period of reconstruction and repair, productive output might be restored with little delay. Moreover, the use of expedient hardening countermeasures during the crisis period before attack could reduce this delay

and increase the survival rate in all areas except around ground zero. Nevertheless, fire could destroy hundreds of square miles around the point of impact, damaging nearly irreplaceable heavy machinery upon which industrial and economic recovery depend. Similarly, much of the surviving human population, protected from fallout, may later perish from fire.

If the fires from a nuclear explosion merely consumed debris in already blast-razed areas, without threatening the surviving population and its resources, then the effect could not be regarded as significant. However, if the fires started in the less severely blast-damaged areas and spread to undamaged tracts, then fire would probably retain its historic role as a city destroyer.

There are some limiting factors, however, to the damage. Ignition by thermal radiation occurs most readily in thin, flammable material; and major fires develop only after some time has passed, during which some of the light-fuel fires may go out but some may spread to more substantial fuels and eventually involve whole structures. Within a few seconds to a minute after the thermal flash from a nuclear burst, the blast wave arrives, and it may blow out many of these young fires. If this possible fire suppression by the blast wave is particularly effective, the number of persistent fires may be dramatically reduced. It could reduce the problem of firefighting to manageable dimensions in areas where blast damage is light, but where fires might otherwise become too numerous to put out.

Such antagonism between blast and fires is largely conjectural; more specific facts and circumstances are needed to confirm or dismiss this effect. Certainly, the blast can totally change the macrostructure of an urban complex from one of discrete structures with discontinuous fuel arrays that force the fire to spread by jumping across open spaces, to nearly continuous fields of debris of variable depths, composition, and compactness, through which fire may spread steadily. This is an unfamiliar situation--not commonly experienced even during the massive air attacks of World War II--a situation about which we can at present only speculate.

Planning for the defense of the United States against nuclear attack must include the best possible understanding of these effects and their interactions. While the potential for incendiary destruction is awesome, the actual threat remains uncertain. If incipient fires produced by thermal radiation from the nuclear fireball were consistently extinguished by the subsequent air blast, in a given set of circumstances, or even if the development of fire were slowed just enough to permit successful firefighting and remedial relocation of the public, the effects might be greatly diminished. To remain ignorant of the possible magnitude of such ameliorative effects of air blast and to neglect their potential remedial benefits is to overestimate the real impact of fire. On the other hand, neglect of the unique potential for fires to threaten human survival and destroy resources, whenever fires would prevail despite blast effects and emergency intervention, leads to planning measures that ignore the stark realities that might someday separate national survival from disaster and defeat.

For a considerable time, the interactive effects of blast and fire have been recognized, but only a limited research effort has been directed toward understanding and quantitatively evaluating them. These effects include the dynamic influences (enhancement as well as extinguishment) of the passage of the air shock over ignited materials and the perturbations in fire growth and spread caused by the residual disarray produced in target elements by blast effects. This research has, to date, provided some insight, but the picture is clouded by seeming contradictions that can only be resolved through additional, and suitably directed, experimental study, complemented by the development of a rational methodology for combined-effects damage assessment.

This report develops the elements of such a program of research. It represents a consensus of many views held by nationally recognized authorities in fire research and protection, blast effects, structures, and related technologies.

II BACKGROUND

Overview

The Five-City Study, conducted under DCPA sponsorship in 1966-67, suggested that fire effects estimated without regard for perturbations due to air blast effects and the damage and fuel redistribution resulting from them could be seriously erroneous.^{1,2} Subsequent experimental investigations^{3,4} tended to confirm this but left the matter unresolved because of the seeming contradictions that arose from piecemeal efforts, poorly coordinated test designs, uncorroborated observations, and other deficiencies. Some descriptive and semiquantitative information about fire spread in blast-damaged buildings resulted from full-scale building burns,^{5,6} and an experimental project on fire spread through debris⁷ provided the first parametrically resolved data and empirically derived relationships available on fire spread through debris of variable depth, density, and composition. From this rudimentary knowledge of the interactive effects of blast and fire, several attempts were made to describe fire effects in blast-damaged urban areas (see Appendix A). At present we have little confidence in these estimates, although results calculated from the independently developed analytical models of the Five-City Study have tended to converge. In a recent attempt⁸ to compute the incendiary outcomes of the atomic bombings of Hiroshima and Nagasaki, the results were broadly consistent with the reported damage.

Of the several critical uncertainties, perhaps the one that overshadows all others is the extinction (or suppression) of fire by air blast since it raises such questions as: how many (if any) fires survive the blast, in what conditions, and in what locations? In short, the combinations of conditions that either suppress primary fire starts--reducing them for a time to a smoldering state--or extinguish them outright cannot be predicted. In an attempt to determine the basic physical mechanisms of interaction between burning objects and air blasts of

varying descriptions, DCPA (in 1973) funded the development of a specially designed Blast/Fire shocktube at Camp Parks, California.⁹ The project was not completed under DCPA sponsorship, but just this year (after a 4-yr break in the activity) DNA has provided funds for completing the facility and demonstrating its research capability. (See Appendix B.) Developments in thermal-pulse simulation offer hope for combined-effects tests at full scale as well as the versatility for parametric studies of the mechanisms of interaction in more idealized representations of fuel arrays, fire processes, and modes of their response to air shock, pressure, and flow. (See Appendix C)

Fire Models

Several competitively developed models for the initiation and spread of fires reached a stage of utility during the Five-City Study.^{1,2,10} To compare the results, these models were applied independently to evaluate fire effects in San Jose, California. The scenario was specified in advance, and a common data base was provided. Blast effects were intentionally ignored except for secondary fire. The damage contribution due to secondary fire was derived from the earlier risk assessment of McAuliffe and Moll,¹¹ which in turn had been developed from historical information. Each participant was encouraged to conduct on-site surveys and to acquire data for his fire model, but little constraint was applied to the method of data acquisition or its level of detail.

The results of the participants were substantially different, enough so that DCPA employed two new contractors to review independently the models and recommend a course of action. The conclusions of these reviews are nearly as valid today as when they were published in 1970, and they are of fundamental importance to future research plans.

The SRI review¹² was limited to the fire-spread aspects of fire modeling and commented on the lack of:

- Mass-fire model development
- Treatment of spread mechanisms besides radiation
- Consideration of effects of fire control countermeasures.

- Development of a spread model for blast-damaged configurations.

The SRI authors were unwilling to select any candidate model to meet future civil defense needs, and suggested the independent formulation of an alternative model.

The Dikewood review¹³ concentrated on fire initiation and early fire development; accordingly, they included the Naval Applied Science Laboratory Fire-start model¹⁴ along with the broader-context models of URS,¹ IITRI,² and SSI.¹⁰ The Dikewood study showed that, even without introducing the uncertainties of blast perturbation, simplifications introduced into the models led to quite different estimates of the probable severity of the initial fire threat. The Dikewood authors were less critical of the fire-initiation models than the SRI reviewers had been of the fire-spread models. In fact, they made specific suggestions as to which model might be used in different applications and how each might be used to provide a framework for specifying needed additional research. They stressed the importance of developing a "good scientific model" before trying to arrive at a simpler operational model.

The Dikewood authors, pointing to the omission of blast interaction in the Five-City Study, commented: "The nuclear attack fire problem is radically different where overpressures cause essentially complete collapse of structures," but they acknowledged that the interactions of blast and fire were not well enough known to permit systematic treatment in any fire model.

In seeking a model amenable to modification that would qualify it as the basic framework for a civil defense fire model, the Dikewood study concluded that both the NASL and IITRI models were strong candidates. In NASL's favor were the following factors:

- Treatment of actual street patterns
- Use of much more use-class-dependent data
- Inclusion of distributions of attenuators at window openings
- Ability of model to summarize results for an entire city
- More accurate treatment of effects of window shades.

Against the use of the NASL model were the following factors:

- Inability to relate the predicted ignitions to building fires or even to room flashover
- Inability to obtain the data required for application to numerous cities
- Inferior modeling of the fireball-shielding and building-window-room interior geometry compared to SSI or IITRI
- Uncertainty concerning validity of the "ignition volume" concept.

Arguments in favor of adopting the basic structure of the IITRI model were:

- Excellent geometrical analysis, resulting in the intensity of received thermal radiation at every point on the ignition plane
- Careful treatment of the "seen" area of the fireball
- Relative ease of applying model to a "new" city
- Compatibility with existing fire-spread models.

Against the adoption of the IITRI model were the following points:

- Application to other use-classes of data specific to residential occupancy
- Lack of treatment of nonnormal azimuthal angles
- Use of precalculated distributions of separation distances and room contents and room sizes
- Assumption that a room flashover implies building burnout.

The Dikewood study found little difference in the adaptability of the two models; thus, major changes would be required if either model were adopted. In their view, the decision depended on such factors as:

- The long- and short-range goals of a national program using the results of any urban nuclear fire study and the relationship between these goals
- Likelihood of funding levels sufficient for continued research and data-gathering
- Urgency associated with developing a working "scientific" model.

Considerations such as these led Miller and his coauthors to make the following recommendations:

- " 1) For immediate use--no time or funds available for model modifications--use the IITRI model. It does a respectable job of treating the important parameters, uses a moderate amount of computer time, and is relatively easy to apply to a "new" city.
- " 2) For short-term development and upgrading--moderate funding available--use the IITRI model, with the following modifications:

allow use of detailed (use-class dependent, where possible) inputs concerning:

- attenuators at the windows,
- size, shape, and sill height of windows,
- distribution of window coverings (flammable and nonflammable),
- fraction of window openings shaded,
- number, type, and arrangement of room contents,
- size and shape of room,
- combustibility of structure,
- shielding by vegetation, as a function of season,
- location of tracts and orientation of streets within them, and
- distributions of separation distances along and across major streets.

in order that the program may include the process of summarizing the results citywide, so that the effects of various attack conditions and defensive actions can be readily assessed.

"These changes require a major rewriting of much of the model, and use of much of the NASL type of data. The suggested model also makes use of something akin to SSI's use of the Gage-Babcock rating system.

- " 3) For long-term development--substantial funding available or time scale of completion not a factor--adopt the NASL model, with the following modifications:

adopt the IITRI procedures for calculation of the irradiated area (or volume) within the room, with proper provision for variable room size and accurate treatment of the "seen" fireball,

incorporate the capability to handle separation distance distributions in two directions,

add the capability to predict room flashover from various ignitions and their proximity to major fuel items (it is at this point that the major research effort will be required),

include the effects of shielding by vegetation,

incorporate the ability to predict building burnout based on room flashover(s) and something similar to the Gage-Babcock index (another substantial research effort required here).

"The development of more realistic fire-start models requires a much better understanding of several disparate phenomena, and incorporation of their effects into the models. The most apparent are as follows:

blast-fire interactions,

shielding phenomena by live vegetation, and
build-up from ignitions into fuel-array fires.

"Blast-fire interactions are not well understood, but blast effects are thought to affect ignition and build-up of fires in a number of ways. Among these are blowout of some ignition points by blast winds, redistribution of ignition points and fuel arrays, generation of secondary ignitions, shield of building from part of the thermal pulse by shock-wave-generated dust clouds, and modification of the nature of fuel arrays and building fuels by shock waves. The rates of intra- and inter-building fire spread are also expected to be modified by blast damage. Much additional work is required to define and understand properly the blast-fire interactions.

"Many urban target areas contain substantial amounts of live vegetation. Possible shielding effects from steam and oil vapors from trees and plants when they are exposed to thermal pulses are not well understood. In some cases the phenomenon is known to be quite effective in shielding against thermal radiation. The application of shielding phenomena such as this to fire-start models is apparent. More research is needed to define this phenomenon and its importance under various conditions.

"The probability of build-up of fires from ignitions in tinder to fuel array fires is not well understood, particularly in the multiple ignition case where fire interactions are involved. This build-up process is obviously crucial to development of structural type fires by intrabuilding spread, and if not well understood could lead to serious misstatements of the severity of the fire problem. More work is needed to better characterize this process.

"Once blast-fire interactions are better understood, the problem of assessing fire starts from an attack on a blast damaged target area could be meaningfully considered. Fire-start models could then be developed that accommodated multiple warhead attacks or target areas and adjacent regions. In this case consideration of fire-induced winds resulting from fires started by an initial attack might be important in considering build-up of ignitions generated by subsequent attacks.

"The extension of fire-start (and fire-spread) models to a multiple-burst case appears to be a rather complex project involving many poorly defined phenomena, and would require much additional research to complete realistically. In many cases, of course, a multiple-burst attack delivered over some period of time is more likely than a single-burst attack, hence such an extension seems justified.

"Additional phenomena whose investigation and inclusion in fire-start models may be of value are:

- local weather characterization in the target area--i.e., probabilities of rain, fog, cloud cover, clear skies, etc., at the time of an attack.

- non-normal incidence of thermal radiation on interior ignition points--its effects and importance, and

- improved characterization of urban target areas, perhaps by the use of aerial photography, to establish distributions of exposed windows, window sizes, street orientations, angles of incidence, exterior fuel arrays, etc., for use directly in fire-start models. Such distributions could be defined as functions of azimuth and elevation angle for various use classes in urban areas and used to predict exposures to thermal pulses from various fireball sizes and locations."

Experimental Data

Effects of Blast on Fire Initiation

The earliest published study specifically directed to effects of nuclear explosions was an experimental investigation of the extinction thresholds of flames in forest fuels under interaction by long-duration flows representing nuclear air blasts.¹⁵ The authors reported evidence that incipient fires in kindling fuels were extinguished by air blasts of low peak overpressures. This study, which was nearly forgotten until the Five-City Study, was subsequently confirmed in general outlines by experiments in the URS shock tunnel,³ although the results were not substantiated in detail.

Using furnished rooms as full-scale simulations in the URS shock tunnel, Goodale found that:

- To extinguish all flames in the test rooms required a threshold value of incident blast overpressure in the range of 1 to 2.5 psi.
- This threshold was not markedly affected by the size of the windows through which the blast propagated; from this observation the author concluded that extinguishment of flame over the surface of interior kindling fuels is not determined solely by particle velocity of the flow near the burning object nor by its duration.
- Kindlings that can support smoldering combustion will continue to smolder following extinction of the flame. Smoldering debris commonly resumed active flaming after delays ranging from minutes to hours.
- High-speed motion pictures revealed at least one instance of flames being swept from the burning surface, apparently by shearless displacement which accompanied shock defraction, suggesting the importance of a sudden (or discontinuous) pressure rise.

The second finding above (and the conclusion associated with it) suggests a corollary that either pressure or pressure change is important to the mechanism of shock extinction. Tramontini and Dahl¹⁵ tacitly assumed such factors were unimportant. The uncertainty about the relative importance of these factors prompted the design of the

blast/fire shocktube, still under construction at Camp Parks, California. In this facility, all of the characteristics of the shock can be controlled and independently varied by the investigator.

The other experimental efforts in the URS series of blast-fire studies provided additional insight into the relative importance of shock, pressure, flow and duration (both positive pressure and flow). Martin et al.¹⁶ investigated shock-induced flows in test enclosures of the URS shock tunnel and confirmed the applicability of theoretical and numerical methods for approximate solutions of such flow problems. Using Melicher's quasi-steady-state theory of flow through openings,¹⁷ Martin et al.¹⁶ concluded that early-time flows into enclosures were insensitive to room orientation and geometry* and that initial inflow velocities were dominated by "side-on" overpressures. This study included detailed numerical calculations of the Eulerian-mechanical description of flows into chambers following shock diffraction. These calculations were used to predict dynamic pressures that were in substantial agreement with experimentally observed flows and also consistent with the approximations afforded by the simpler computations of the quasi-steady-state model.

Two subsequent studies conducted by Goodale^{18,19} in the URS tunnel are noteworthy. In 1971, Goodale¹⁸ explored the effects of higher overpressures (to a maximum of 9 psi) on the residual smolder that had consistently been observed after the blowout of flames at 2½ psi. The higher overpressures did not produce a smolder-extinction counterpart to the blowout of flames. No trend was evident between 5 and 9 psi. Cushions filled with polyurethane foam and kapok failed to smolder after flame blowout at all overpressures. Goodale concluded that cotton batting may be especially susceptible to smoldering and, therefore, items

* Clearly, filling times (and, hence, rates of decay of inflow velocity) do depend on the relative sizes of rooms and openings, but the early-time velocities--which are apt to determine whether extinguishment occurs or not--are determined mainly by the initial pressure differential.

containing this substance may represent a special hazard that could be eliminated by changing this material. In a separate study,¹⁹ Goodale tried to quantify the hazard due to burning curtain fragments transported by the flow through windows following shocks of lower overpressure. (All experiments were conducted at 1 psi to avoid blowout.) He concluded that the transport of burning fragments by blast can be extremely hazardous, but that this mechanism depends critically upon the time the blast wave arrives relative to the stage of the burning curtains or drapes, which in turn is a function of the weight of the fabric comprising the window hangings. He recommended further investigation of these dependencies because of the great incendiary potential represented by this synergistic interaction between thermal ignition and blast, even at relatively large distances from ground zero.

A more reliable method was needed to anticipate the delay between thermal exposure and the peak-burning phase of hanging fabrics. Given this predictive capability, plus better statistical data on the distribution and frequency of various kinds and weights of fabrics used as window hangings in urban occupancies, one could then confidently compute frequencies of significant fires in urban interiors resulting from the combination of thermal ignition and the subsequent transport of burning curtain and drape fragments by blast from nuclear explosions.

In a later study,²⁰ Wilton et al. used the URS "Long Duration Flow Facility (LDFF)" and found that the placement of the burning item in the room, relative to entries and exits, and fuel type were the critical variables for extinguishment. Both cellulosic and synthetic materials were investigated. Some items were confined and others unconfined; all were flaming at the time of simulated blast arrival. Under the experimental conditions (i.e., flows equivalent to those that would result from reflected pressures, external to the chamber entrance, of 2 to 4 psi^{*})

* Note, however, that in the LDFF a true pressure discontinuity is not produced and the pressure differentials are mainly dynamic.

extinguishment occurred only when samples were located in regions of high flow velocities (near entrances, exits, and in some geometries, near the center of the room); permanent extinction occurred only in lightweight fuels. In heavier fuels, complete extinguishment never occurred; rather, flaming subsided to a smolder, rekindling to flame within a few minutes.

During Operation MIXED COMPANY, Wiersma and Martin²¹ participated in a 500-ton TNT explosion to demonstrate extinguishment by shearless displacement and to seek the scaling relationships for the interactions governing the process. Shearless displacement of the flames did not occur, nor were any of the fires extinguished, not even at the 5-psi station. The horizontal fuel beds of liquid hydrocarbon, mechanically stabilized with a gravel "wick," were essentially flush with the ground, and the nonideal shock behavior near the ground might account for the unexpected behavior. After the test,²² the shock was reported to be appreciably degraded near the ground surface. Thus, the fuel beds probably experienced a gradual pressure rise, and potential flow accompanied by an already-established turbulent boundary behind the shock. They also might have been subjected to a substantially reduced overpressure. Moreover, since a liquid hydrocarbon was used instead of the usual solid fuels of urban enclosures, the result could be due in part to the relatively high vapor pressure and low latent heat of vaporization of the hydrocarbon fuel.

At the 120-ton high-explosive detonation of Misers Bluff, SRI assisted BRL in an attempt to establish at least one experimental point of high confidence. A well-anchored cushion of vinyl-covered polyurethane foam, one-half of which had been covered with terrycloth to enhance smolder, was positioned well above the ground surface and exposed to a thermal fluence of nearly 20 cal cm^{-2} and, 2-sec later, a 7-psi shock. The motion-picture sequences showing the shock interaction are not yet available, but observation after the shot indicated that the fire had been initiated in both halves of the cushion by the thermal exposure and then completely extinguished by the subsequent shockwave.

Effects of Blast Damage on Growth and Spread of Fire

Little is known about the growth and spread of fire in blast-damaged buildings. Some reasonable inferences can be drawn from models of ventilation effects on fire behavior in enclosures and configuration factor concepts of radiation heat transfer, but these are largely unsupported by experiment. The pioneering studies by Shorter et al.²³ and by Labes²⁴ established a pattern for subsequent full-scale tests of burning buildings. In a comparative study of damaged and undamaged buildings, Vodvarka²⁵ found that the blast-damaged structures burned in one-third to one-half the time required for undamaged structures.

In a similar study at Camp Parks, California, Butler,²⁶ using a series of nearly identical barrack sections as test specimens, compared the fire dynamics of one partially collapsed unit with uncollapsed counterparts. The burning rate of the partially collapsed unit increased more slowly and decayed more rapidly than the fires in the undisturbed units. As in the IITRI experiments, the duration of active burning was substantially shorter.

In subsequent tests, the fire behavior in totally collapsed structures was dissimilar to anything previously experienced with structures. The fires were characteristic of debris fires, spreading at a rate determined largely by the ambient wind but influenced by the degree of brokenness of the structural components and the state of compactness of the remains.

Debris fires were conducted by IITRI in response to the concern of DCPA over fire effects on shelters.²⁷ These studies showed that fires within debris piles, typical of the remains of residential occupancies, delivered their maximum heat flux to the shelter exterior within the first hour and subsided rapidly thereafter. Toxic gas generation was also short lived. On the other hand, deep debris piles, representative of the destruction of total structure, produced slow-burning fires generating gases that tended to hug the ground.

To date, the most definitive study of fire behavior in debris was a DCPA-funded joint effort between SRI and NSWC.⁷ The study was conducted in two phases: the first in the laboratory; the second, involving large-scale burns, in the field. In both phases, debris fire behavior was observed; measurements were made on the rates of fire spread, durations of active flaming (i.e., residence times), and concentrations of gas effluents; and the dependence of the observed and measured debris fire characteristics on wind speed and on variables in debris makeup were investigated.

The rates at which flames spread through debris were strongly dependent on ambient wind velocity and on the nonfuel-to-fuel ratio of the debris. The rates of spread were only moderately dependent on fuel loading and almost independent of fuel-size distribution. Debris composition and compactness also appeared to affect flame-spread rates, but these variables were not studied independently nor extensively. Carbon monoxide yields averaged about 100 lb per ton of combustible content of the debris, independent of the conditions and circumstances of burning.

Concluding Remarks

This section has briefly reviewed the current state of blast/fire interaction technology. More than an exposition of our understanding of the problem, this section indicates how little is confidently known and points up the major deficiencies that exist and that require additional research.

III NATURE AND SCOPE OF THE PRESENT STUDY

Conference Format

To formulate a plan of action for advancing our understanding of blast-fire interactions we convened a working conference of assembled authorities representing the highest level of expertise and authority in the requisite disciplines. These conferees were brought together in a "Gordon Conference" atmosphere, conducive to uninterrupted attention to the problem and a full and free exchange of ideas and background information. The meeting was held at the Asilomar State Park and Conference Grounds on the Monterey Peninsula in California. The agenda and list of attendees are presented on the following pages.

Workshop Approach

To encourage and direct development of specific program planning elements, the meeting was structured into three workshops. Following the general session, the attendees were assigned to separate workshops to formulate plans of action and to report back, at appropriate times, to the general session. The three workshops and their assignments are described below.

Workshop 1: Physics of Fire-Shockwave Interactions (Leader: Harold Brode; Recorder: William Taylor)

The concern of this workshop was the various potential mechanisms of shock/flow interactions with burning fuels that might act to extinguish the fire or to otherwise significantly modify the combustion process. Attention was given to a parallel development of experimental tests and theoretical models or concepts. Physical hypotheses that could be tested experimentally were postulated. The applicability of existing test facilities and anticipated test opportunities were also reviewed and evaluated.

ASTILOMAR 1978

AGENDA

May 21 Sunday evening (after dinner):

Keynote--"Objectives for U.S. Preparedness and their
Implications for Civil Defense Design Options"
by Clifford E. McLain, Deputy Director, DCPA
(See Appendix D).

May 22 Monday morning:

General Session--Blast/Fire Perspective
Fire Effects of Nuclear Explosions (Martin)
DNA Programs--Collateral Effects (Kennedy)
DCPA Programs--Population Protection;
Shelter and Relocation (Bensen, Kerr)
BRL Programs--Shocktube and HE Tests (Taylor)

Monday afternoon:

General Session--Structuring the Workshops
Goals set and assignments made;
Adjourn to workshops for remainder of afternoon.

Monday evening:

General Session--Technology Update
Structural Response Program at Dice Throw
(Carl Wiehle)
Casualty Prediction (Andy Longinow)
Thermal Simulation for Large-Scale Air Blast
Experiments (Bill Taylor)
Fire Propagation Model: A Continuity Approach
(Gekirge--See Appendix E)

May 23 Tuesday morning: Workshops Continue

Tuesday afternoon:

General Session: Midpoint Review of Workshop Progress
Resume Workshop Activity

May Tuesday evening: open

May 24 Wednesday morning Continue Workshop Activity, Prepare Summaries

General session: Presentation of Workshop
Summaries
Adjournment

DCPA BLAST/FIRE CONFERENCE

ATTENDANCE LIST

Raymond S. Alger (Ray) SRI International Menlo Park, CA 94025	Tom Kennedy Defense Nuclear Agency Washington, D.C. 20305
Norman J. Alvares (Norm) Lawrence Livermore Laboratory Box 808, L-Stop 442 Livermore, CA 94550	James W. Kerr (Jim), Emergency Operations Systems Division RE(E0) Defense Civil Preparedness Agency Washington, D.C. 20301
David Bensen (Dave) Hazard Evaluation & Vulnerability Reduction Division-RE(HV) Defense Civil Preparedness Agency Washington, D.C. 20301	Anatole Longinow (Andy) IIT Research Institute 10 W. 35th Street Chicago, Ill. 60616
Harold Brode (Hal) R and D Associates P.O. Box 9695 Marina del Ray, CA 90291	Stanley B. Martin (Stan) SRI International Menlo Park, CA 94025
Clay P. Butler (Pres) 1427 Floribunda Burlingame, CA 94010	H. L. Murphy H. L. Murphy Associates Box 1727 San Mateo, CA 94401
H. M. Cekirge Basic Technology, Inc. 7125 Saltsburg Road Pittsburgh, PA 15235	Clifford E. McLain (Cliff) Emergency Operations Systems Defense Civil Preparedness Agency Washington, D.C. 20301
Francis E. Fendell (Frank) R1/1038 TRW One Space Park Redondo Beach, CA 90178	Richard Park (Dick) National Council of Radiation Protection & Measurements 7910 Woodmont Avenue Bethesda, MD 20014
Thomas C. Goodale (Tom) SRI International Menlo Park, CA 94025	John Rempel SRI International Menlo Park, CA 94025
Kenneth Kaplan (Ken) 30 White Plains Court San Mateo, CA 94402	William Taylor (Bill) Ballistic Research Laboratories Aberdeen Proving Grounds Maryland 21005

Thomas Waterman (Tom)
IITRI
10 W. 35th Street
Chicago, Ill. 60616

Carl Wiehle
Defense Intelligence Agency
Att: CKW DB-4C2
Washington, D.C. 20301

Steve J. Wiersma
International Power Technology
506 Oakmead Parkway
Sunnyvale, CA 94025

C. Wilton (Chuck)
Scientific Services, Inc.
1536 Maple
Redwood City, CA 94064

Workshop 2: Blast Response of Urban Elements and Descriptions
of the Resulting Fuel Disarray.

(Leader: Thomas Kennedy; Recorder: H. L. Murphy)

In this study, we were less interested in responses of structures, per se, than in how the blast wave interacts with them and their contents to modify fire initiation, growth, and spread. Thus, the emphasis was on the diffraction of shockwaves into rooms, room-filling flow mechanisms, (as these may perturb fuel contents and incipient fires) and changes in structural geometry and integrity (as these may affect fire growth and intrastructural spread), and the generation and distribution of debris (representing fuel disarray and a possible continuum for interstructural fire spread).

Critical pieces of missing information were to be identified and used to establish requirements for pertinent research activity. Where such research might complement and extend on-going or planned research programs, recommendations to include the additional tests were made.

Workshop 3: Fire Dynamics in Blast Perturbed Fuel Arrays

(Leader: Raymond Alger; Recorder: Richard Park)

The concern of this group was divided into three parts: enclosure fire behavior, debris fire behavior, and blast-caused (secondary) fires. Among the questions posed were the following:

- Given a fire start, what changes in enclosure characteristics would bring about changes in fire behavior?
- When does an enclosure cease, effectively, to act as an enclosure?
- Given a fire start in debris, what parameters govern behavior?
- How well do we need to describe debris?

The group was also to identify the inputs needed to describe fire growth and decay in the urban target, the destructive environment, and its history, above and below ground. Having identified the needed inputs the group was to formulate a program for acquiring this information.

Finally, they were to reexamine the question of secondary fires and recommend further study, if appropriate.

Output Statements of Workshop 1

The Fire/Shockwave Problem

A limited scenario may place the fire/shockwave problem in perspective. Imagine a large metropolitan area having several major industrial installations, air fields, and port facilities, all of which may be subject to specific targeting in an attack. Although the immediate surrounding urban areas may suffer extensively from blast damage and fires beyond the heavily destroyed area, much of value might be saved if it can be saved from burning. The area beyond a blast peak overpressure of 2 psi might be such an area. From a 5-megaton air burst, the area exposed to less than 2 psi lies 8 miles and farther from the point of explosion. Some 200 square miles of damage may lie inside that circle. In the area 8 to 13 miles away, substantial thermal fluence will fall (from 10 to 60 cal/cm², dependent on the visibility and distance), enough to start many fires.

In that vast area (300 square miles), if the blast wave of 1 or 2 psi blows out the fires that the thermal pulse started, much of value could be spared the ravages of fire, and many homes or shelters saved for the survivors. More important, many of those who would otherwise perish in the fires might be spared. Some firefighting could become practical in such areas. Civil defense planning could be directed to saving people and houses in large areas otherwise destined to burn. In the suggested example of a 5-MT explosion, only 30 seconds are required for the blast wave to reach the 2 psi point (8 miles). This is ample time for people to take cover to avoid flying glass and other objects, but not a great deal of time for fires to spread.

Experiments simulating the effect of a blast wave on a radiation-initiated fire indicate that the blast may either enhance the fire or suppress it. The number of experiments, and the instrumentation used, make any definitive statement at this point unjustified.²⁸ Nevertheless.

a long-standing (quarter-century-old) uncertainty now may be asked with more urgency and more justification: Is there not a critical range of overpressure (say, 2 to 5 psi) for which the blast may extinguish fires initiated by the thermal radiation? Of course, this is a multiparameter problem involving the physical and chemical properties of the fuel, its size and orientation, the state of burning at the time of shock arrival, and the thermodynamic and dynamic environment to which the fuel is exposed after shock arrival. A more complete enumeration is given below. Despite its complexity, it is a well-defined problem with significant implications for the fire threat accompanying thermonuclear attack. Further, we have the technology to resolve the uncertainty.

Our Current Understanding of Blast Effects on Fires

As with many effects of nuclear weapons, little direct information is available; much of what we know about the effects of blast on fires is indirect and inferential.²⁸ Early atmospheric tests with nuclear explosives suggested some blast suppression of ignitions. Further, shock tube¹⁵ and high explosive tests indicated that blast waves of modest strength (greater than $2\frac{1}{2}$ or 3 psi) could blow out the flames of many fires, but were likely to fan rather than extinguish glowing ignition.^{3,21} In fact, if the blast were too short in duration or too weak in overpressure (and hence wind velocity), it might actually fan the fire.

The type of fuel can also make a difference: Fires from liquids or gases may be harder to blow out than the fires from solid fuels.²¹ A sofa ignited only seconds earlier may have its flames blown out by a blast wave, but the quick creation of char and the persistence of glowing ignition may lead to a subsequent ignition and the continued growth and spread of the fire.³ Curtains may be completely consumed and drop to the floor before the blast reaches them, thus spreading less flaming material than would be the case if the active-burning phase were longer or the time before blast arrival were shorter.^{19,29} A

well-established fire from a previous burst may provide copious fire brands and cause many more new ignitions when struck by the blast wave from a subsequent burst.

Many parameters can play some role in the processes of blast/fire interaction, but we are unlikely to know them fully. In any event, the scant information available from experiments or from Hiroshima or Nagasaki³⁰ does not allow much more than speculation about the relative importance of such factors. Nevertheless, a fairly complete (but not exhaustive) list of parameters is presented in Table 1.

Table 1

FACTORS EXPECTED TO PLAY A ROLE IN THE
EFFECTS OF BLASTS ON FIRES

Physical

Overpressure (range)

Wind or partial velocity (flame removal, convective cooling of fuel)

Increased oxygen partial pressure (can increase burn rate)

Drag pressure or fuel movement (disruption of fuel arrays)

Yield

Duration of blast winds and overpressure

Flame displacement

Time of blast arrival (after ignition)

Time of thermal pulse (duration)

Spectrum of thermal pulse (surface temperatures of fuel)

Peak intensity and total thermal pulse

Debris distribution

Height of burst

Amount of heat on fuel (direction and intensity of irradiance)

Direction of blast

Thermal precursor effects on blast winds and direction

The significance of precursor shocks and particulate effects on radiation, etc.

Fuel arrays

Orientation relative to gravity

Dimensions (height, length, width) i.e., geometrical configuration

Reflectivity (color)

Surface roughness (texture)

Position relative to other fuel arrays

Shadowing, shading, attenuation, e.g., effects of curtains,
windows, etc.

Position relative to blast openings or reflections from walls

Susceptibility to blast transport, drag properties

Micrometeorology

Visibility (dust, smoke, cloud cover, haze)

Natural winds

Air temperature

Solar preheating

Humidity

Chemical Kinetics

Fuel properties

Ignition threshold

Absorptivity (opacity, albedo)

Thermal conductivity

Moisture content

Heats of vaporization

Thickness

Heat capacity

Density

Mass transpiration rates

Burn character

Depth of char

- Persistence of char
- Heats of combustion
- Radiation spectrum, emissivities
- Smoke properties
- Constituents and amount of combustible vapor emitted
- Distance of flame from fuel surface

Dynamic blast-fire interaction factors

- Boundary-layer growth and thickness influences on flame separation from fuel
- Relation between wind velocity and snuffing
- role of fuel bed length and orientation
- Blast flow along or counter to flame, plume, vapor trail direction
- Flow in rooms, reflections, reversed flow
- Movement of heated air or hot gas from absorbed thermal or flames
- Multiple-burst environments multiply the complications

Unsatisfactory as the present technology seems, in view of the progress made in other branches of combustion sciences, our understanding is not so retarded that a decade will be required for results to evolve from the research. Rather, within 3 to 5 years, the blast/fire interaction problem could be well in hand if we pursue a systematic and complementary program of experimentation and theoretical development.

As supporting evidence for this optimism, we can cite, for example, the recent progress on wind-aided flame spread.³¹ We can now predict accurately the rate of flame spread (if any) along a combustible, partially burning sample suddenly exposed to a hot sustained flow that

traverses still-nonpyrolyzing portions of the fuel array. This problem involves coupling of gas and solid phases, with dependence on at least two spatial coordinates and time. One part of the fuel array evolves combustible vapors that burn in the air-vapor mixing zone near the solid surface, where these vapors escape the solid, while the remaining, cooler part of the array is not yet heated enough to produce vapor fuel. The demarcation separating the two parts moves across the array as time passes, and the unsteady progress can be modeled theoretically. The complex coupling between gas-phase heat release in the resulting diffusion flame and endothermic pyrolysis in the solid was too difficult to handle mathematically only as recently as 2 to 3 years ago. This Stefan-type problem, with its split boundary condition along the critical interface, has now been solved mathematically.³¹ While it does not incorporate all of the difficulties of shockwave interactions with burning objects--especially the pressure discontinuity and highly transient fluid flow--it offers hope that the lagging theoretical aspects of the problem can be brought quickly abreast of the experimental developments if a concerted, complementary approach is used.

Research Program

The research program has three key objectives:

- ° Investigate the physical/chemical mechanisms for idealized fuels (simple geometries and known properties) interacted upon, during free burning, by ideal shocks of controlled characteristics.
- ° Develop analytical models that can predict the effects of idealized blast/fire interactions, and extend the models to predict nonideal effects, such as interactions between diffracted shocks and charred and porous solid fuels.

Describe the sustained primary ignition field for the fire-development models.

The research plan outlined herein addresses the questions that civil defense planners ask about the probability of fires occurring and spreading when a large nuclear weapon is detonated. Typical of such questions is the following: "Will the blast wave enhance or extinguish a fire within a structure that is in the low overpressure region." The plan first treats fires from noncharring fuels and shows how important blast flow velocity is in regard to flame speed. This investigation highlights the importance of boundary layers and may help explain the different effects observed in the MIXED COMPANY and URS tunnel experiments. In URS tunnel experiments, photographs showed a shock sweeping the flame from the fuel and extinguishing it. The threshold of extinguishment is associated with a pressure level (2 psi) but the result cannot be applied to a free field case (the MIXED COMPANY Gravel wick experiment) which showed that free-field pressures up to 5 psi would not extinguish a noncharring fuel.

Despite the many differences between the two experiments, our intuition strongly suggests that extinguishment cannot be related to overpressure alone. We do not believe that weak overpressure, static pressure only, would extinguish a flame from a noncharring fuel. In fact, minor effects such as heat of compression and an increase in available oxygen would tend to support combustion. We do believe that the air flow velocity associated with an overpressure, will, if it moves swiftly relative to flame speed, extinguish a flame. The flame must of course move out of the fuel bed; otherwise reignition may occur. Even so, reignition can occur with the displaced flame out of the fuel bed if vapor is contiguous to both the fuel and the flame. Such a condition could hardly exist in a turbulent boundary layer that may exist in some shock interaction problems.

While a close approximation to a full-scale thermonuclear test is desirable, the value of less expensive, more rapidly executed, and easily repeated tests in laboratory facilities is to be emphasized. Only under such controlled testing can the matrix of tests required for a multiparameter problem be carried out. Existing facilities include sources of high radiative exposure, facilities exploiting geometric scaling by use of pressure levels, subsonic ducts permitting the sudden onset of severe thermal environments, and shock-tube and blowdown tunnels that tailor the amount and duration of overpressure. Even if these facilities can accomplish only very partial modeling, the partial checkout of the theoretical model is well worthwhile. As the complexity and sophistication of experiments increase, one can conceive of large fuel arrays ignited by (simulated) thermal flashes and exposed to the full blast from large high explosive charges or from the conical shock tube or other large blast simulators. Such full-scale simulation can assure the veracity of piecemeal modeling and prevent oversights.

The development of a workable theoretical basis for predicting blast effects on fires would be of great utility in the face of so many variables. As noted earlier, theoretical modeling should not be delayed, since theory appears to be lagging experimental work. Predictive theory is important because a validated prediction forms a more reliable basis for extrapolation and strategy guidance.

The testing of all possible fuels, arrangements of fuel arrays, yield ranges, burst heights, etc., would require a formidable program without the guidance of theoretic models. To facilitate the prior (or at least parallel) development of theoretical models, early experimental programs should include simple, idealized flame and blast sources that can be readily simulated in theory. The program should have all significant processes included (though not necessarily at the outset) and should have a consistent level of approximation throughout. The goal is not to have, for example, sophisticated chemical-kinetic rates and mechanisms, but naive fluid-dynamical flow-field representation.

Proposed Experiments

The following experiments are proposed for this study:

- Conduct flameout studies on noncharring fuels
 - Determine blowout velocities when under various boundary-layer conditions, unheated air passes over a short length of fuel
 - Repeat the measurements for heated air
 - Measure extinguishment or intensification of similar ideal fires as a function of overpressure and duration for ideal shocks
 - Examine effects of fuel properties, amount, and distribution on extinguishment or intensification
 - Determine wall reflection and opening defraction effects
- Conduct flameout studies on charring fuels
 - Perform an idealized solid fuel and shock wave study on char depth versus shock characteristics and the time of arrival
 - Investigate a range of char types and the effects of surface properties
 - Examine the boundary-layer effects and the influence of the flame position with respect to the boundary layer
 - Measure effects of shock/flow
 - Study effects of fuel geometry, arrays, and orientation
- Perform fanning and rekindling experiments
 - Examine rate of firespread versus shock strength
 - Study transport and reignition for glowing embers in a blast wave
 - Consider role of blast wave in providing fuel for the fire
- Determine large-area ignition thresholds
- Investigate multiple burst effects
 - Observe effects of expanded delay between first thermal exposure and shock, e.g., deep charring

- Examine ignition and extinguishment conditions in mixed debris
- Consider effects of smoke on air density
- Verify suitability of heat sources (e.g., oxy-propane torch, Al-O₂ balloon, pyrotechnics) for simulating thermal pulse ignition under different experimental circumstances
- Correct model deficiencies found in course of experimental program, including nonideal interactions
- Develop and verify model to permit prediction of extinguishment/intensification effects in full-scale field tests of urban-target simulations.

Conclusions

Mass fires from nuclear attacks could be the major cause of damage to cities. Any further research on the interactions between the blast wave and thermal ignitions should evaluate the relevance of such interactions to the three phases of defense: "before attack," "during attack," and "after attack." Much can be done before an attack: combustibles can be moved or covered, thermal shields can be erected, firefighting crews and materials can be prepositioned, crews can learn what to look for (smoldering furniture, charred clothing, etc.). In the few tens of seconds between the thermal flash and the arrival of the shock, little can be done, but the time between multiple bursts may allow some emergency actions. As a consequence of this research, we may establish that the bulk of exterior fires are extinguished by the blast, and that the interior fires are the ones that will persist after the attack.* Such research could increase the usefulness of fire prevention and firefighting procedures.

Many parameters can be readily investigated in shock tubes and in laboratories. As a check against the inadvertent oversight of factors

* The converse is also credible and can be plausibly argued from current evidence.

not represented in idealized exposures, large-scale tests of structures and typical contents with flash-initiated fires and high explosive blasts could provide a worthwhile conclusion to the program.

We have seen evidence that blast waves can extinguish some ignitions; but, surely the accompanying air flow can also fan glowing embers and spread firebrands from well-established fires. The circumstances leading to the suppression or intensification of fires need more careful delineations and some further experimental differentiation.

The nature of the threat to major U.S. industry from nuclear attack is a major consideration in the cost and strategy of the preparedness measures to be undertaken. The blast/fire interaction not only influences the techniques and personnel expertise used to protect existing manufacturing facilities, but also may affect future alteration and expansion plans of heavy industry. The time to initiate the required technical investigation is at the outset of any resurgent civil-defense activity.

Output Statements of Workshop 2

Single Building Studies

Single buildings can be analyzed with present tools, knowledge, and computer programs to determine their resistance to blast, their breakup, and distribution of their debris. To accomplish this, buildings need to be classed by type of construction, but this can be done without difficulty

State-of-the-art techniques consist of computer programs as well as a considerable body of experimental data that can be used to analyze the dynamic response and collapse of various building elements and whole buildings. These programs have been used with blast-loading techniques to predict the collapse of elements in a variety of National Shelter Survey buildings. These procedures can roughly predict the amount of debris from collapsing building elements, but because of unknowns in the loading on each wall of a complex building geometry (as well as the effect of collapsing walls on subsequent loading), the problem can only be bounded, not solved explicitly.

Programs are also available to analyze the elastic and inelastic response of structural frames. At present these programs do not include collapse mechanisms, but the output can be used to reasonably estimate the probability of frame collapse. The translation of debris produced by collapsing building walls can also be predicted with current programs. These programs require input in the form of the wall velocity at collapse and the size of fragments. The final disposition of the postulated fragments can also be predicted with these models, but to date this capability has not been experimentally verified.

Building Contents

The distribution and breakup of contents caused by an entering blast wave can be predicted for certain idealized situations. If the only opening to a room is in the wall that is struck head-on by the blast wave, the subsequent flow (including entrainment of light debris within the room) can be approximated with existing tools. These methods include mathematical analysis (RIPPLE and/or simple roomfilling) verified by reference to results of past experiments (URS tunnel, BRL model basement, and DICE THROW structures 1 and 2). This information may also serve to describe the flow adequately for purposes of predicting extinguishment of primary fires and creation of secondary fires.

In the more general case, however, when the openings are in different walls, the analyses are appreciably more complex, and new analytical methods will be needed to handle the situations involving intersecting flows. The same is true of flows through connecting rooms. The presently available methods are probably not good enough to adequately define debris distributions.

Similarly, we have adequate tools to treat the collapse and breakup of a wall struck head-on and to analyze the conversion of structural elements into debris. The principal weakness is a lack of understanding of how fragmentation occurs in a sufficient variety of wall types. Also experimental verification of the debris translation model is required.

Structural debris, when it occurs, would likely be superimposed on room-content debris.

Building interaction. The debris in a builtup area depends on the nature of the buildings in the zone in question. Parameters entering the problem include:

- Relative location of buildings
- Sizes
- Structural systems
- Relative strengths
- Orientations relative to the blast direction
- Building contents
- Times to failure/collapse

The blast wave is expected to be altered by these parameters, thereby producing a debris pile substantially different from that produced by the same buildings if located in the open, whose individual debris elements are simply superimposed. This problem is not well understood, and the importance of individual parameters is not well known. Good tools are not available, but crude estimates can be made using existing tools.

Multiple buildings. The extension of single-structure blast loading information into a city complex has not been realistically accomplished. Previous studies used models of structures of uniform size. New work is needed to investigate nonuniform-sized structures (shadowing), blast wave propagation down streets (channeling) and other phenomena that could affect structural loading and subsequent debris distribution within a city. Again, proven tools are not available, but crude estimates can be made.

Multi-burst effects/response. The air blast and ground shock environment that results from two or more closely timed detonations is at present not well understood; the Defense Nuclear Agency (DNA) is working

now to provide environment definition data. The response of a given building to two or more loadings is to some extent understood; however, the uncertainties associated with the first loading are compounded by their impact on the starting point assumptions for the beginning of the second loading calculations, making the second and succeeding loading calculations less and less credible. No data exist on multidetonation-formed debris and, to our knowledge, no attempts have been made to examine analytically debris formation from more than one detonation.

The study of multiburst-formed debris is not thought to require high priority at this time, since the state of knowledge from single bursts is weak. As work advances with respect to single-burst effects, multibursts may be considered.

Research Program

A two-path program is proposed. One path will continue the logical development of computational and experimental techniques to predict the translation of interior contents and structural debris and their distribution. These are defined as complementary efforts and are discussed in the following subsection.

The main thrust of the program, which is outlined in Figure 1, is a step-by-step research program to develop structural damage and debris data required for the blast-fire interaction program. The first two steps of the program, Analysis of Individual Structures and Analyze City Complex (Crude Cut), can realistically be accomplished in 18 months to make possible rough approximations of the debris distribution within a city. The first step, Analysis of Individual Structures, includes the following:

- Develop structural damage and debris contours for each of the building categories/types as a function of air blast overpressure. These contours will be derived using available computational techniques that will need to be refined and automated.
- Estimated time of completion of this task is 12 months; however, portions of the work, by specific building type(s), will be available in 9 months.

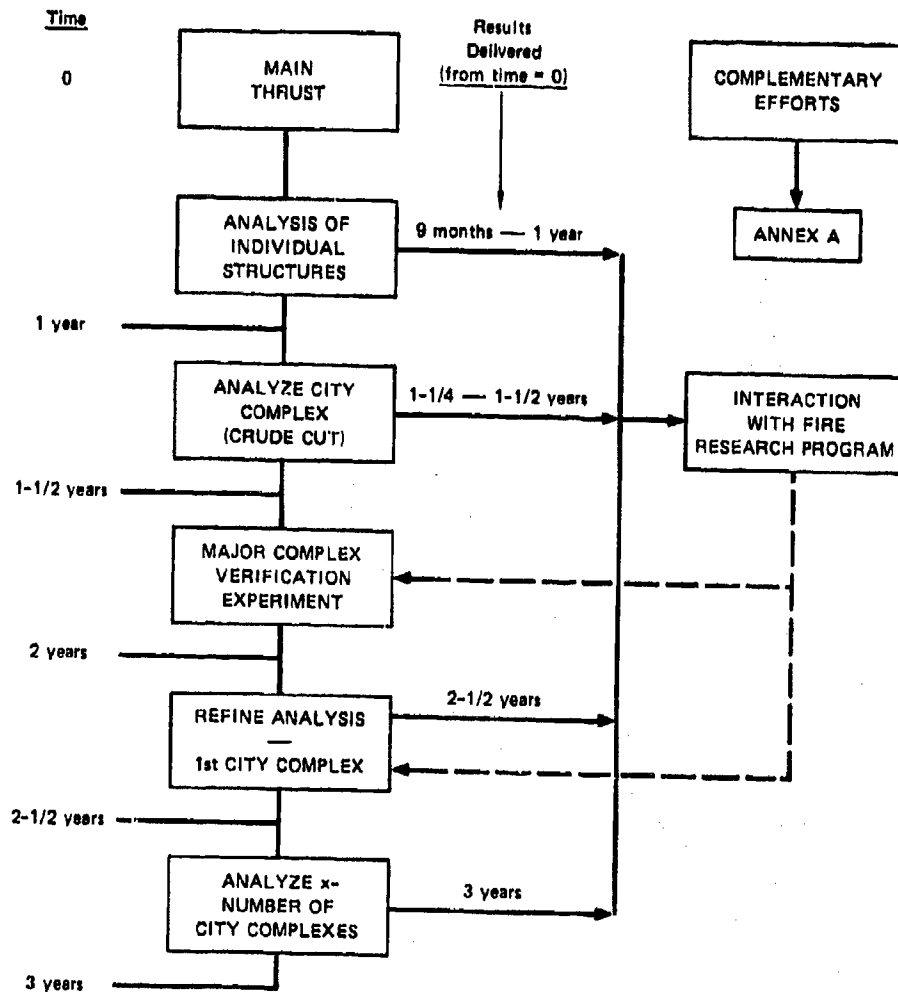


FIGURE 1 BLAST-STRUCTURES-DEBRIS RESEARCH PROGRAM

The second step, Analyze City Complex (Crude Cut), uses the results from the first step to approximate roughly the debris distribution within a targeted city. Currently, San Jose, California is suggested because of the excellent data base available. This step is very important since it yields early major data for fire researchers, and also points out the areas where further extensive research is required.

The third step, Major Complex Verification Experiment, may consist of one large or several small experiments; they will be better defined during the early phases of the program, but are planned to include a multistructure small building test during the Misty Castle event, shock tube tests of structures and structural elements, and laboratory tests. This task should be finished by the end of the second year.

Based on the results of the tests and inputs from the fire researchers plus results from the Complementary Efforts a more accurate debris distribution pattern will be developed for the first city complex, San Jose; Figure 1 shows this step, Refine Analysis - 1st City Complex.

The final step, Analyze x-Number of City Complexes, applies the developed technology to other cities to test the systems, determine differences among cities, and furnish a broad data base for use by the blast/fire research community. The total program is estimated to take 3 years; a preliminary cost estimate for the first two steps and related complementary efforts is \$500,000 to \$600,000.

Complementary Efforts

The principal complementary efforts listed by Workshop 2 are given below:

- Debris interaction: investigate the importance of multiple debris-debris interaction on the final debris pile
- Drag and lift coefficients: develop experimentally a list of drag and lift coefficients for representative debris pieces, including furnishings.

- Debris catalog: develop and computerize a debris catalog for a set of buildings by floor level.
- Interacting flows: using hydrodynamic codes and shock tube experiments, develop an engineering method to predict flow patterns and drag on contents in a room with openings on adjacent and/or opposite walls.
- Multiroom flow patterns: develop engineering methods for predicting flow through a complete floor plan of interconnected rooms.
- Oblique incidence: calculate loading and clearing of pressure fronts reflected at oblique incidence from exterior walls and roofs in a manner analogous to current methods for estimation of head-on reflected blast waves.
- City complexes: improve our understanding of diffraction of blast waves through, and perturbations of flow over, city complexes exposing models in shock tubes and at high explosive field tests. These models should reflect the size variation and distribution of structures present in cities or in an actual candidate city. (Some shock tube efforts to study drag on rectangular blocks in tandem and a few pressure distributions among uniformly distributed identical rectangular blocks have been reported.)
- Trajectory verification: develop confidence in results of calculation of debris trajectories by experimental verification. Currently used drag and lift coefficients, as well as spring constants controlling debris-ground interactions, are pure extrapolations from other fields of engineering. Past full-scale high explosive experiments may provide some evidence for this verification of the documentation is adequate.
- Hysteretic behavior: extend available resistance functions for exterior and interior wall elements to include hysteretic effects, so that dynamic response can be predicted for reversal of load function on walls.
- New wall types: develop resistance functions for wall types that have not been previously treated, but are important to blast/fire interaction.
- Structural properties: perform laboratory tests to determine dynamic material properties to supplement available data (e.g., timber elements such as floors and stud walls.)
- Mixing of debris types: study interaction of debris between various types of buildings, e.g., industrial buildings and residences.
- Frame analysis: examine available dynamic inelastic building frame programs for possible application to nuclear weapon effects, and modify candidate program to include collapse mechanisms.

- * Model use: determine how small a scale can be used for structural and debris models and yet provide adequate degree of confidence in resulting data.

Output Statements of Workshop 3

Objectives

Chronologically, the description of fires in perturbed fuels covers the period following the rearrangement of structures and their contents by the blast and the initiation of serious burning. Organizationally, the description of the sustained ignition field* (from the Workshop 1 program) and the description of the debris field (from the Workshop 2 program) are combined to provide the basis for predicting the subsequent fire behavior. The objectives of these fire predictions are threefold: (1) to estimate the threat to people, (2) to determine the effects on property, and (3) to assess the potential remedial benefits of countermeasures. If the evacuation plans have been executed successfully, the people threatened are those key individuals remaining in shelters and others in the target area; so the prediction concerns their requirements for survival and the restrictions imposed by the fire on their performance of assigned duties. Two aspects of fire effects on property are of concern; first, the loss of supplies, materials and essential records, and second, the damage to industrial facilities and equipment that determines the country's recovery potential. The effects of countermeasures on fires also have two facets: the control or limiting of the extent of damage; and the development of procedures that expedite the restoration of facilities and equipment.

Approach

Two major steps are involved in reaching the Workshop 3 objectives: first, the fire threat must be defined (i.e., the temporal and spatial

* Although Workshop 3 included secondary fires in its area of concern, such fires clearly constitute a portion of the population of initial fire starts.

characteristics of the thermal field, the products of combustion and pyrolysis, and the consumption of combustibles); second, an analysis must be made of the response of people, property, and countermeasures to the threat. The fire behavior emphasized will vary somewhat according to the distance from ground zero. For example, in regions of sparse ignition where the fire is growing, attention will be focused on ignition susceptibility and the rate and pattern of fire spread. In regions of full fuel involvement, the burning rate and fire intensity become most important. The products of combustion (smoke, heat, gases and vapors) define the threat to be ameliorated with appropriate countermeasures.

Fire behavior predictions can be based on empirical data, analytical models, or a combination of the two. Such predictions cover flame-spread rates, burning rates, and the liberation of energy and products as a function of the burning fuel and its environment. Table 2 lists the important parameters involved in such predictions.

Table 2

PARAMETERS PERTINENT TO THE PREDICTION OF FIRE BEHAVIOR

Fuel

- Type of structures and contents
- Amount: size and loading of structures
- Chemical and physical properties, particularly the thermal properties
- Geometry or arrangement, i.e., size of individual fuel elements, their distribution in size and space, and degree of destruction

Environment

- Air: wind velocity, direction, and flow pattern
- Heat sources and sinks: noncombustibles, amount, size, and distribution
- Thermal properties of nonfuels
- Compactness or porosity of debris

Areas of Knowledge and Ignorance

In general, our knowledge of fire behavior is most complete for simple fuel arrangements burning in environments where the ventilation conditions and thermal sources and sinks are also simple and well-defined. Complex arrays of combustibles and noncombustibles or varying ventilation conditions soon expose our ignorance. The matrix in Table 3 indicates these areas of strength and weakness in the knowledge of fire behavior. The table lists the major categories of structures found in typical urban areas. Each category defines the preblast fuel and environmental parameters. After the blast, the structures are rearranged in various degrees, ranging from broken windows and light damage (column 2) to piles of nearly homogeneous rubble (column 6). The upper left corner of the matrix (namely, single family buildings with little damage such as would be encountered in the 1-psi region and beyond) represents the condition where information is most complete and probably adequate for predictive purposes. Past work such as the IITRI room and house burns and NOL-SRI house burns coupled with current activity at NBS, JPL, IITRI, and SRI provide considerable experimental data and analytical insight for this case. Also, the existing fire records contain sufficient historical data to cover most of column 1, that is, the undamaged or virtually undamaged structures of various types.

Moving to the right along the single-family-house line, the knowledge becomes increasingly sparse until the lowest point is reached in columns 4 and 5. Column 2 covers damage to the room contents ranging from slight to a complete stirring of the fuel. While information is sparse about the well-stirred fuel case, it is probably adequate, particularly after the fire spreads beyond the room of origin. At that point, the mode of buildup in the room becomes of little concern and the fire has progressed beyond the limits of self-help. In column 3, the structure has been opened sufficiently to permit flames to spread from room to room, to expose combustible structural members normally shielded by the wall coverings, and to increase the ventilation. One SRI fire of this type gives an inkling of the burning characteristics

Table 3

MATRIX OF FUEL CATEGORIES AND DEGREES OF DAMAGE

	1. Undamaged	2. Windows broken; contents light damaged to well stirred	3. Structure; standing but opened up - new ventilation paths	4. Significant collapse; fuel still on site	5. Off site debris; individual piles	6. Homogeneous mix of debris
1. Woodframe and brick-veneer residence	F	E	L	L	L	F
2. First three floors with weak walls	E	F	P	P	P	L
3. Fourth and higher floors with weak walls	F	P	P	P	P	P
4. Steel and reinforced concrete, framed	F	F	?	?	?	?
5. First three floors of building with strong walls	F	F	?	?	?	?
6. Fourth and higher floors of building with strong walls	L	?	?	?	?	?
7. Massive masonry buildings	L	P	?	?	?	?
8. Industrial, heavy manufacturing	F	?	?	?	?	?
9. Industrial, refineries and chemical	F	?	?	?	?	?

Symbol

E = Extensive data

F = Fair

L = Limited data

P = Poor, not much data

? = Uncertain

but leaves us in a poor position for predictions. Similarly, little data exist for columns 4 and 5 but the large number of possible fuel distributions lead to less certainty regarding fire behavior for these damage cases. A little more information is available for column 6, row 1 because of the IITRI shelter studies under debris fires and the SRI observations on thin layer debris pile fires. Adequate information is available to assess the effects of fires on shelters but not to predict fire spread in the uncertain configurations involving fuel and nonfuel.

The taller buildings represented in rows 2 through 7 provide the potential for much deeper debris piles than those that have been studied. Consequently, there is much uncertainty about flame spread rates and patterns, burning rates, and the products of combustion.

The industrial categories represented by rows 7 through 9 are also areas of ignorance; however, the variations from one type of plant to another probably require a case-by-case examination instead of the averaging process employed for dwellings.

Spatially, the area of ignorance is the doughnut between the hole of complete collapse and the rim of few ignitions. This picture assumes that for some distance around ground zero, sustained ignitions, both primary and secondary, are sufficiently concentrated to eliminate the concern of fire spread over significant distances. The blast-fire interaction studies should define the boundary of the hole, and the debris field work should describe the corresponding fuel-nonfuel situation. If the homogeneous mix of debris exists only in the doughnut hole, column 6 in Table 3 can be neglected from the standpoint of fire spread.

At distances corresponding to the light damage in column 2, i.e., broken windows and some rearrangement of the room contents, the existing ability to predict the occurrence of the sparse primary ignitions is probably adequate. A substantial body of ignition data exists for this relatively unperturbed case. Also, the historical information on fire spread in American cities is largely for undamaged buildings.

The intervening doughnut remains the principle area of importance, with respect to both fire starts and fire spread. Descriptions of both the ignition field and the debris fields are essential to the study of fire behavior in this region.

Suggested Program Elements and Priorities

The proposed program contains five major elements and each element involves several tasks. Since all the elements are essential to the stated objectives, the priorities are assigned to best use the prerequisite information about the ignition field and debris field as it arrives from Workshops 1 and 2. Several tasks can proceed concurrently.

Describe the fuel bed. This element involves a joint effort between the disciplines represented in Workshops 2 and 3 and consists of two tasks:

- Task 1: Determine the detail required to describe the debris field in the doughnut area.
- Task 2: Establish the minimum structure-degree of damage matrix (Table 3) adequate to cope with the fire problem in typical cities.

Workshop 3 must determine the degree of detail significant to predictions of fire spread rates and burning rates based on models that can cope with the size and complexity of a nuclear incident. An appropriate median position must be found between a degree of resolution that accounts for every combustible item, its environment, and thermal physical properties and a uniform fuel field that allows for no preferential fire spread. Since these decisions are required early in the Workshop 3 program, this task (definition of the fuel bed) should commence immediately.

Describe the ignition field. Two tasks are incorporated in this element:

- A determination of the primary ignition pattern based on the criteria established in fire-blast studies of Workshop 1.
- A description of the secondary ignition field based historical evidence from natural and man-made disasters.

Thirteen years have passed since the McAuliffe-Moll 1965 report¹¹ on "Secondary Ignitions in Nuclear Attack." Consequently, some additional data have been developed in this area where information is rather sparse. Also, this period has witnessed a rapid development in analytical techniques such as decision analysis and failure mode and effects analysis, which optimize the conclusions that can be reached with statistically poor data. A review of the historical evidence with these modern techniques should substantially increase the reliability of the secondary ignition predictions.

Determine fire characteristics for the various structures in the intermediate and severe damage states. This element is particularly concerned with damage levels indicated by columns 3, 4, and 5. Again, the characteristics include fire spread, burning rate, and production. Three tasks are involved:

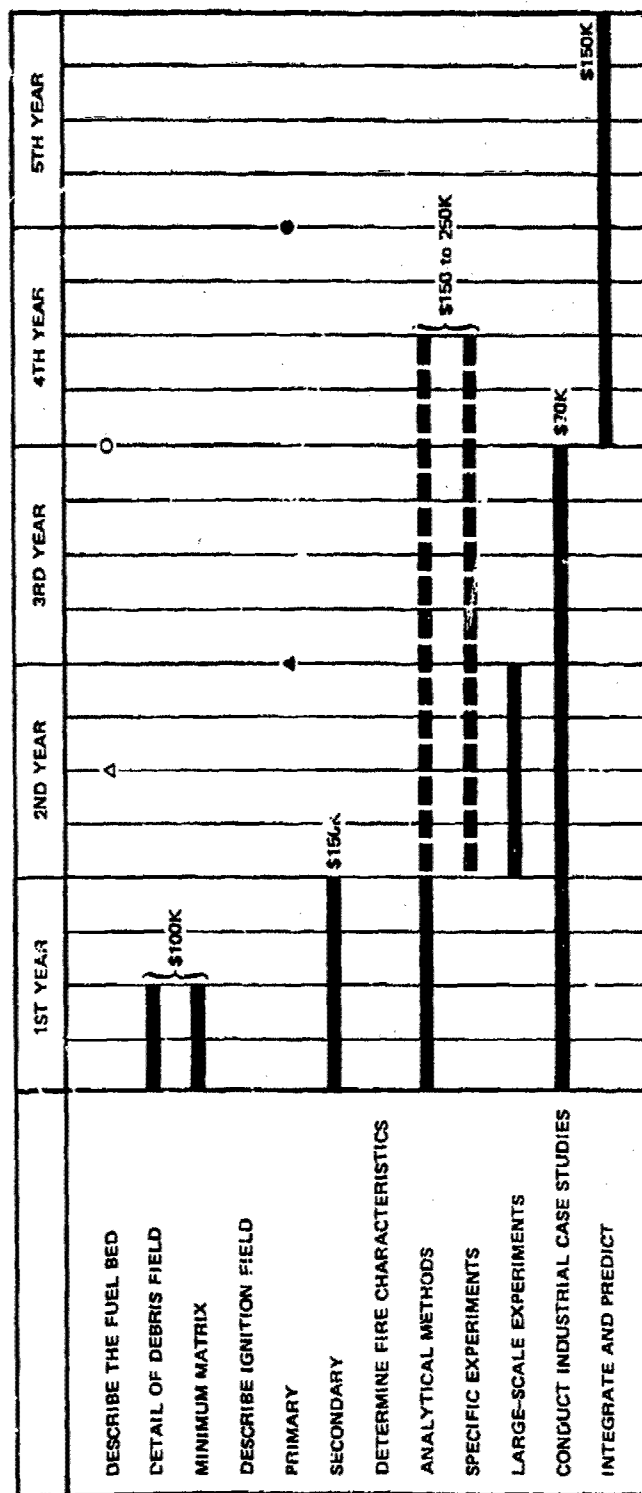
- Develop and expand analytical methods and models to accommodate the fuel and environmental situations in Table 3.
- Develop specific experiments to answer limited questions essential to the model development and validation.
- Conduct a few large scale experiments for inspiration and guidance in developing and verifying the analysis.

Conduct case studies of the industrial fire problem. This element is concerned with the fire problems anticipated in the industrial area of a city under nuclear attack. Because of the wide divergence in construction and fire hazard, it appears desirable to consider the various industrial categories individually (e.g., petroleum refineries, chemical plants, heavy manufacturing plants, light manufacturing plants).

Integrate the individual structure and industrial plant fire behavior into a prediction for a typical urban complex. This element pictures the fire threat to be used in evaluating effects on people, equipment, and countermeasures.

Program Schedule and Cost Estimate

The following milestones and cost analysis (Figure 2) assumes the program is completed in 5 years and that information from Workshops 1 and 2 will materialize at various intervals, first in preliminary and then in final form. A steering committee or lead laboratory is needed to oversee the total program and ensure that the proper interface is made between the various program elements.



REQUIRED INPUTS

- ▲ Preliminary Ignition Field From Workshop 1
- Final Ignition Field from Workshop 1
- ▲ Preliminary Definition of Debris Field From Workshop 2
- Final Definition of Debris Field From Workshop 2

FIGURE 2 MILESTONES AND COSTS: WORKSHOP 3

IV PROGRAM RECOMMENDATIONS

Program Significance and Scope

Previous sections of this report have shown that presently unresolved questions about the relevance and importance of various interactions of blast waves (and their effects) on fires (and on the potential for fire spread to increase damage, destruction, and life loss) are major obstacles to defense planning and countermeasure preparation; they can even impact National Security decision making at the highest levels. Concisely stated, these uncertainties substantially preclude any reliable quantitative estimates of the outcome of nuclear attack on the United States and of our capacity to survive and recover from such an attack.

We have identified the technical deficiencies that prevent the development of a theoretical or analytical basis for predicting, within orders of magnitude uncertainty, the additional contribution fire effects can make to the direct effects of nuclear explosions in or near urban complexes. We have also developed a logical, analytical framework for structuring and performing a research program to eliminate the technical deficiencies or reduce their contribution to the uncertainties in damage prediction to an acceptable level. A vital consideration in program formulation--both in preplanning and in reviewing progress and redirecting effort throughout the course of the program--is the question of realistic goals in terms of reduction of uncertainty to acceptable levels. What constitutes an acceptable level of uncertainty?

Since we can obviously never know with certainty the outcome of any future nuclear incident, our preparations to deal with such an event must include some degree of uncertainty, for uncertainties will always exist no matter how well we understand the underlying cause-and-effect relationships. Given this inherent uncertainty, we must realistically moderate our requirements for the resolution of technical uncertainties. Clearly, the level of understanding of any one technical issue should be commensurate with

its practical utility and its relative importance to the ultimate national objectives, and the whole should be consistent with the perceived threat. Guided by these principles, we have identified near-state-of-the-art research tasks that promise significant immediate returns and, with modest investment, can provide within 2-to-3 years a technologic base that is a prerequisite to reliable damage prediction.

Beyond this, the program elements can be seen in outline only. One basic limitation is the state of the art of analytical modeling. Present modeling concepts appear valid, sufficiently diverse to accommodate a range of requirements for output detail (given appropriate input detail), convenient in format, and compatible with current strategic planning programs. Their deficiencies stem mainly from the assumptions employed to reduce their complexity. In most cases, simplifying assumptions have been used in model development without due regard for their effects on the analytical results. Therefore, an obvious requirement is research directed toward the testing of assumption sensitivity, the elimination of questionable assumptions, and, where possible, the replacement of contrived algorithms with established physical relationships. Then, as the damage-prediction models improve, we will be afforded better and more frequent glimpses of the true magnitude of the fire threat, the importance of the remaining uncertainties that continue to cloud our view, and the fundamental limitations introduced by our modeling concepts. The improving perception will also guide our decisions about how much more to invest in research and how to invest it effectively; in time, it will permit us to judge the "return on investment" for proposed counter-measures and intervention strategies.

The program, as outlined in the following statement of objectives and recommended approach, is regarded as optimal in scope and level of activity for achieving the required upgrading in technology within 5 years.

Program Objectives

The ultimate purpose of the research program is a sound technological basis for the choice and cost/effective design of a defense system to protect the public and minimize the destruction of property and national resources by the incendiary effects of nuclear explosions, and thereby to enhance the recovery of the nation. The prerequisite is a reliable capability to predict fire effects and the mitigating actions of preparedness countermeasures. Therefore, our technical objective will be the development of one or more good-confidence, analytical models of fire behavior and incendiary-damage production. At present we anticipate a need for three separate models:

- A general urban fire distribution/spread model, applicable mainly to areas of light-to-moderate structural damage; intended to give time-phased frequency distributions of burning and burned-out structures for each different urban use-class (or structural-type) tract as functions of distance from ground zero (or location in an arbitrary coordinate system).
- A "hole-in-the-doughnut" model, applicable to areas of totally collapsed structures, continuous debris fields, and innumerable fires; intended to deal with fire intensity versus time only, spread of fire being included implicitly only.
- A specific-resource vulnerability model, applicable to a single structure, facility, or resource threatened by fire exposure within the context of a general fire description, provided by one of the foregoing models.

Approach, Scheduling and Funding

Choice and/or development of these models is the first order of business because the models provide a structure for the program, and, through sensitivity analysis, they can provide quantitative and defensible criteria for establishing priority assignments for program elements. Through periodic updating and iteration, the funding levels and scheduling of task completion requirements are revised to reflect

the best current assessment of program status and needs for changes in direction. At each iterative step, the models are modified to reflect the latest advances in the state of knowledge of blast/fire interactions. Thus, the models keep pace with the state of the art, and the level and direction of effort is consistent with user requirements for operational planning, choice of countermeasure strategies, and technical backup to justify program funds and to guide policy and decisionmaking.

We further recommend that some elements of the Five-City Study be reactivated to serve the purposes of this iterative development.

We also recommend that the procedure of model development and its sensitivity-analysis application as a tool for program management be initiated with emphasis on the general-distribution/spread-type model, since this is a well-developed technology. Already, recommendations have been offered for further development and civil defense implementation. The initial stress should be given to processes of fire initiation since these contain some obviously crucial uncertainties that must be resolved before much progress can be made with modeling of the later stages of fire growth and spread.

The underlying technology (whose development should parallel and support the model's) ranges from observation of physical phenomena and the derivation of basic physicochemical principles to development of algorithms and empirical approximations and the application of these to model calculations and verification of results with full-scale tests and simulations. The separate requirements for background technology in blast effects and fire effects are fairly symmetrically distributed over the range from fundamental to applied, but, since some of the blast work is supported independently for other purposes, the fire portion of the program outlined here requires a somewhat disproportionately higher level of support.

The optimal-level FY1979 program breaks down as follows:

1. Blast analysis of individual structures	\$ 200K
2. Complementary blast studies (drag/lift experiments, hydro-code calculations of flow in enclosures, initial experimental verification)	100
3. Initiate search for/and development of blast/fire predictive models	200
4. Sensitivity analysis/program planning	60
5. Repeat secondary-fire analysis	100
6. Shocktube studies of blowout mechanisms	200
7. Initiate development of theory for shock/fire interaction (ideal fuels/geometries)	50
8. Preparation for participation in Misty Castle	10
Total for FY1979	\$ 920K

This would logically be followed in FY1980 by the following:

1. Initial blast analysis of city complex	\$ 150K
2. Verification experiments (Misty Castle) on structural response, debris production and distribution, persistence of ignition and fire behavior in blast-damaged targets	500
3. Complementary blast studies (continued from FY79)	100
4. Analytical development of blast/fire models (continued from FY79)	100
5. Experimental complement to blast/fire model development	100
6. Sensitivity analysis/program planning and review (includes contractor conference)	50
7. Experimental verification of doubtful ignition thresholds (large areas of mixed fuels)	50
8. Shocktube studies of blast-fire interactions (continued from FY79)	200
9. Development of theory of blast-fire interactions (continued from FY79)	50
Total funding for FY80	\$1,300K

This program is expected to culminate with one or more full-scale simulations of urban/industrial complexes subjected to the combined blast and fire effects of a nuclear explosion, possibly involving a high-explosive test series dedicated to this purpose. As the program elements and requirements become better defined, experimental and verification test activities will increase, requiring more facilities and increased funding. At present, however, the funding requirements cannot be estimated with confidence.

Finally, a problem of this magnitude and complexity requires a program of at least 5-years duration, involving a wide range of interdisciplinary research activity conducted at a moderately large number of government agency laboratories and private research institutes, appropriately assisted at times by industrial contractors. A program of this scope requires strong, consistently applied monitoring and coordination to ensure that the obtainable goals are significant, to maintain a level of performance that is consistent with need, and to synchronize complementary or dependent elements. These requirements point to the need for the designation of a lead laboratory to conduct some key across-the-board elements of the research and to direct and coordinate the variety of complementary tasks done by contractors and other contributors. We urge the adoption of the lead laboratory concept.

REFERENCES

1. S. Martin, R. Ramstad and C. Colvin, "Development and Application of an Interim Fire-Behavior Model," Final Report, Work Unit 2538C, URS 674-3, URS Systems Corp. 1811 Trousdale Drive, Burlingame, California (April 1968).
2. A. N. Takata and F. Salzberg, "Development and Application of a Complete Fire-Spread Model: Vol. 1 (Development Phase)," Final Report, Work Unit 2538B, NRDL-TRC-68-36, IIT Research Institute (June 1968).
3. T. Goodale, "Effects of Air Blast on Urban Fires," Final Report, Work Unit 2534I, URS 7009-4, URS Research Co., San Mateo, California (December 1970).
4. S. J. Wiersma and S. B. Martin, "The Nuclear Fire Threat to Urban Areas," Final Report, DCPA Work Unit 2561A, SRI Project PYU-8150, Stanford Research Institute, Menlo Park, California (April 1975).
5. F. J. Vodvarka, "Full-Scale Burns in Urban Areas: Part 1, Fire Spread Between Structures," Final Report, OCD Work Unit 2534E, IITRI Project J6009, IIT Research Institute, 10 West 35th Street, Chicago, Illinois 60616 (June 1969).
6. C. P. Butler, "Measurements of the Dynamics of Structural Fires," Annual Report, OCD Work Unit 2561A, SRI Project PYU 8150, Stanford Research Institute, Menlo Park, California 94025 (August 1970).
7. S. J. Wiersma et al., "Characteristics of Fires in Structural Debris," Final Report, DCPA Work Unit 2561C, Naval Surface Weapons Center, White Oak, Maryland (January 1975).
8. S. Martin et al., "The Impact of Fires Produced by Tactical Nuclear Weapons," DNA 4214T, Science Applications, Inc., 1200 Prospect Drive, La Jolla, California 92037 (December 1976).
9. S. Martin and T. Goodale, "Shocktube for Blast-Fire Interaction Studies," Summary Final Report, DCPA Work Unit 2563B, SRI Project PYU 2026, Stanford Research Institute, Menlo Park, California (August 1974).
10. J. W. Crowley et al., "FIREFLY, A Computer Model to Assess the Extent of Nuclear Fire Damage in Urbanized Areas," Final Report, Work Unit 1614B, Systems Sciences, Inc., 4720 Montgomery Lane, Bethesda, Maryland 20014 (May 1968).

11. J. McAuliffe and K. Moll, "Secondary Ignitions in Nuclear Attack," OCD Work Unit 2534A, Stanford Research Institute, Menlo Park, California (July 1965).
12. L. W. Weisbecker and H. Lee, "Evaluation of Systems of Fire Development," Final Report, OCD Work Unit 2619A, SRI Project ECU-6250, Stanford Research Institute, Menlo Park, California 94025 (August 1970).
13. R. K. Miller, M. E. Jenkins, and J. A. Keller, "Analysis of Four Models of the Nuclear-Caused Ignitions and Early Fires in Urban Areas," DC-FR-1210, OCD Work Unit 2619B, Dikewood Corp., Albuquerque, New Mexico 87106 (August 1970).
14. J. Bracciaventi, "Fire Start Capabilities of Nuclear Detonations in Urban Areas--Predict Model," Work Unit 2534B, Naval Applied Science Laboratory, Brooklyn, New York (September 1969) (AD 700 694).
15. V. N. Tramontini and P. R. Dahl, "Forest Fuels Blast Studies," Report 53-15, University of California, Los Angeles, California (June 1953).
16. S. B. Martin et al., "Effects of Air Blast on Urban Fire Response," URS 705-5, Final Report of OCD Work Unit 2534F (May 1969).
17. J. F. Melichar, "Propagation of Blast Waves into Chambers," BRL-MR-1920, Ballistic Research Laboratories (March 1968) (AD 672476).
18. T. Goodale, "An Attempt to Explore the Effect of High Blast Overpressure on the Persistence of Smoldering Combustion in Debris," Summary Report, Work Unit 2534 (Mod. P616-1), URS 7030-6, URS Research Co., San Mateo, California 94402 (December 1971).
19. T. Goodale, "The Ignition Hazard to Urban Interiors During Nuclear Attack Due to Burning Curtain Fragments Transported by Blast," Summary Report, Work Unit 2534 (Mod P616-1), URS 7030-5, URS Research Co., San Mateo, California 94402 (December 1971).
20. C. Wilton et al., "Blast/Fire Interaction, Blast Translation, and Toxic Gases," URS 7239-11, DCPA Work Unit 2563A (July 1976).
21. S. J. Wiersma and S. B. Martin, "Evaluation of the Nuclear Fire Threat to Urban Areas," DCPA Work Unit 2561A, Annual Report, SRI Project PYU 8150, Stanford Research Institute, Menlo Park, California 94025 (September 1973).
22. MIXED COMPANY Results Meeting, Santa Barbara, California (March 13-15, 1973).
23. G. W. Shorter et al., "The St. Lawrence Burns," Research Paper No. 98, National Research Council of Canada, Division of Building Research (June 1960) (Also published in Quarterly of the National Fire Protection Association, Vol. 53, No. 4, pp. 300-316, (April 1960).

24. W. G. Labes, "The Ellis Parkway and Gary Dwelling Burns," Fire Technology, Vol. 2, p. 287 (November 1966).
25. F. J. Vodvarka, "Full Scale Burns in Urban Areas," Final Report IITRI Project J6009, OCD Work Unit 2534E (June 1969).
26. C. P. Butler, "Measurements of the Dynamics of Structural Fires," Annual Report of SRI Project PYU 8150, OCD Work Unit 2561A (August 1970).
27. A. N. Takata and T. E. Waterman, "Fire Protection for Basement Shelters in New Construction," Final Report for Period 1 July 1970 through 31 December 1971, OCD Work Unit 1135A, IIT Research Institute, Chicago, Illinois (31 December 1971--draft).
28. S. Martin "DCPA Blast/Fire Conference - State of the Problem Background and Preconference View," SRI International, Menlo Park, California (21-25 May 1978).
29. S. Martin, "The Role of Fire in Nuclear Warfare," DNA 2692F, URS Research Company, 155 Bovet Road, San Mateo, California 94402, Final Report (August 1974).
30. U.S. Strategic Bombing Survey, Effects of the Atomic Bomb on Nagasaki, Hiroshima, Japan, Physical Damage Division, October, November 1945 (June 1947).
31. G. R. Carrier, F. E. Fendell, and P. S. Feldman, "Wind-Aided Flame Spread Along a Horizontal Fuel Slab. I. Without Radiative Transfer," Engineering Sciences Laboratory Rept. 30740-6001-RU-00, TRW Defense and Space Systems Group, Redondo Beach, California.

Appendix A

DCPA BLAST/FIRE CONFERENCE

STATE OF THE PROBLEM:

Background and Preconference View

21 - 25 May 1978
Asilomar, California

PREFACE

The following material is intended to serve as background information for the attendees of the 1978 DCPA Conference on blast/fire interactions. It consists of descriptions of (1) fire initiating processes resulting from nuclear explosions and (2) the consequent damage produced by combined blast and fire effects in urban areas, both of these believed to be representative of the state of the art. It will be one of the purposes of the conference to skeptically examine the foundation of this technology and the validity of its conclusions. Its positive results should be a technically defensible program of research to provide important missing information.

INTRODUCTION

The combined blast and fire effects of nuclear explosions in urban areas have been recognized and documented as operationally significant and important to strategic planning. These effects include (1) the dynamic influences of the air shock passing over ignited materials i.e., fire enhancement or extinguishment, and (2) perturbations in fire growth and spread caused by the blast induced disarray in the target.

Quite literally, the perceived importance of fire as a nuclear-weapon effect swings from minor to major depending on which of several credible assumptions are used to assess the dynamic and residual in-

fluences of air blast on combustible targets. Several critical uncertainties are:

1. Threshold air-blast conditions for the extinction of fires initiated by thermal radiation.
2. Process of rekindle in fuels perturbed by blast.
3. Effects of structural damage on the processes of fire growth and spread.
4. Descriptions of debris fields in sufficient detail to permit calculation of fire-spread rates and burning rates.

These uncertainties and their importance to strategic defense concerns are developed in the following sections.

FIRES FROM NUCLEAR EXPLOSIONS

At the time of a nuclear explosion, materials in and around urban structures are ignited, initially by thermal radiation emitted by the fireball (primary fires) and subsequently through mechanical damage and displacement caused by the ensuing blast wave (secondary fires).

For many years, primary fires have been thought to be the dominant cause of incendiary damage from nuclear explosions, far exceeding in number the fires from secondary causes. Their incendiary reach has

frequently been identified with the distances to which free-field thermal radiation exposures extend that are at least equal to ignition thresholds for newspaper. This is now known to be a serious overestimate of the threat.

The primary fire threat to urban targets is the result of ignition of building contents and is affected very little by exterior ignitions in most circumstances. Excessive amounts of exterior kindling fuels are required to ignite a sound wooden structure. Rarely are such quantities to be found in residential areas while in industrial and commercial areas wooden buildings are uncommon. Ignition and burning of exterior fuels depends heavily on weather while interior fuels are relatively insensitive to it. Moreover, such a high frequency of internal ignitions is anticipated that exterior ignitions appear to add little to the problem in most urbanized areas.

The ignition of a single item of kindling fuel in a room by no means assures the fire involvement of the room. Generally speaking one or two combustible furnishings such as an overstuffed chair, a couch, or a bed must be ignited (either directly or through the agency of adjacent kindling fuels) and burn vigorously to cause "flashover" of a typical residential room. Newspaper and other materials of similar ignition susceptibility are very common items of interior fuels and are frequently found on and near items of furniture. Nevertheless, extensive surveys of contents and arrangements of ignitable interior materials in buildings representing a variety of occupancies consistently show that damaging fires will seldom result unless radiant exposures are sufficient to ignite directly the more substantial items such as upholstered or material-covered furnishings. These radiant exposures can be two to three times as large as newspaper ignition thresholds.

The secondary fires, those caused by the blast wave, are expected to occur in the relatively infrequent situations where suitable combination of coexisting fuels and energy sources are brought into favorable (to ignition) contact by blast damage or displacement. McAuliffe and Moll¹ estimate this, from retrospective evidence, to be on the order of two fires in 100 buildings (perhaps 80 building fires per square mile in moderately built-up areas) wherever the peak overpressure exceeds 2 psi. This may underestimate the frequency for some industrial occupancies, but there is no mechanistically-based rationale for expecting more secondary fires in urban targets in general.

At higher blast overpressures, the fire situation is further complicated by structural collapse, ejection of building contents and partitions, and the deposition of debris in the open, between buildings, to provide a path for fire spread as well as a threat to survival and an impediment to emergency action. Some of this debris may already be burning or it may even be ignited by belated exposure to that portion of the decaying thermal pulse that follows the arrival of the blast wave. Evaluation of incendiary threat in areas of such high overpressures may seem largely academic since the prospects for survival of the expediently sheltered population seem so poor. On the contrary, survival rates to the initial effects (i.e., air blast, missiles, whole-body translation, prompt radiations, flash burns) can be good. Thus the possible prolonged and delayed effects of fire are all the more important.

Moreover, the fire response of the entire urban target is a dynamically coupled process in which the fire behavior of one area may influence--even govern--the behavior elsewhere. Thus the fire response in the heavily damaged center of the target (the so-called "hole-in-the-doughnut" area) is an important, inseparable part of the dynamic interrelationships between ambient weather; target demography and topography; perturbations in the local meteorology caused by the explosion and the convective

influences of the resulting fires; the development and spread of the fires; and the ameliorating effects of fire control activities. The questions of whether or when isolated fires will become mass fires can only be answered confidently by considering what is going on inside the hole-in-the-doughnut along with what is going on in the "doughnut" itself, that is, in the areas of the target where blast damage is less severe. Actually, and unfortunately, next to nothing is known for certain about the fire picture inside the "hole." (This aspect of damage assessment is reviewed in a recent SRI report.²)

We can, however, speak with some confidence about the early-time response of the doughnut during the interval of time between the explosion and the arrival of the blast wave. We can make quite adequate predictions about the number, types, and positions of materials that will be ignited by the thermal pulse and with some confidence forecast the distribution of the resulting fires in time and space--that is, if we neglect blast effects. If we attempt to include blast effects we run into serious trouble, and yet the picture is not only incomplete without them, but it may also be almost totally erroneous. It is, nevertheless, instructive to begin with the early-time fire picture and to neglect, for the time being, the awkward problem of blast-fire interactions.

Tinder-type materials--those capable of both sustaining ignition when exposed to modest radiant heat loads and igniting in turn more substantial fuels such as furniture and wall panels--are abundant among the contents of urban interiors. Their ignition thresholds typically range from 3 or 4 cal cm⁻² for the thinnest materials exposed to the short, intense pulse of low-to-nominal yield nuclear airbursts, to as much as 50 cal cm⁻² or more, for the thicker materials exposed to the long-duration pulses of megaton explosions. Surveys of urban interiors reveal a fair degree of regularity in the frequency distribution of such kindling materials when classified according to their ignition thresholds.

Although the mean number of ignitable fuels per room at any given level of radiant exposure depends on a variety of factors such as land use and building occupancy, geographic location of the city, and weapon yield and burst height, the resultant calculation of fire-initiation probability is not sensitive to most of these factors. It can be shown that few, if any, situations will develop sustained fires when radiant exposures of the interior fuels are less than about $20 \text{ to } 30 \text{ cal cm}^{-2}$. This statement is really only valid for megaton-yield explosions at low altitude, but the scaling relationships for yield and burst altitude show a weak sensitivity only. For free-field conditions, thermal exposures required for significant numbers of sustained primary fires occur at distances to which blast-wave peak overpressures of only 2 to 3 psi are expected. However, interior fuels rarely, if ever, experience anything like free-field exposures.

There are two different mechanisms by which thermal exposures are reduced. First, attenuation by the atmosphere and window coverings (i.e., glass, screens, blinds, nonopaque drapes) reduces the transmission of radiant intensity by a fairly well defined (and predictable) fraction. Atmospheric attenuation is a function of the condition of the atmosphere and the distance between the fireball and the target location. It is related to the visibility (as commonly estimated at airports) sometimes called the visual range. If we regard the transmission of thermal energy to be 100 percent on a clear day (visual range of 12 miles or more), then on a day of medium haze (3-mile visibility) we will experience only about half the clear-day thermal exposure. Thus, we will not expect to suffer many fires at distances less than those corresponding to free-field exposures of perhaps 50 cal cm^{-2} or more. When the atmosphere is especially hazy or smoggy, it will dominate the effects reducing thermal transmission. In particular, whenever the visual range is significantly less than the clear-day incendiary reach, the distance to which fires will extend is roughly equal to the visual range.

Windows and window coverings will further reduce fire incidence. Twenty to sixty percent reductions in exposure are typical. Therefore, we may not anticipate a serious fire problem at much less than free-field exposures of 100 cal cm^{-2} except on very clear days.

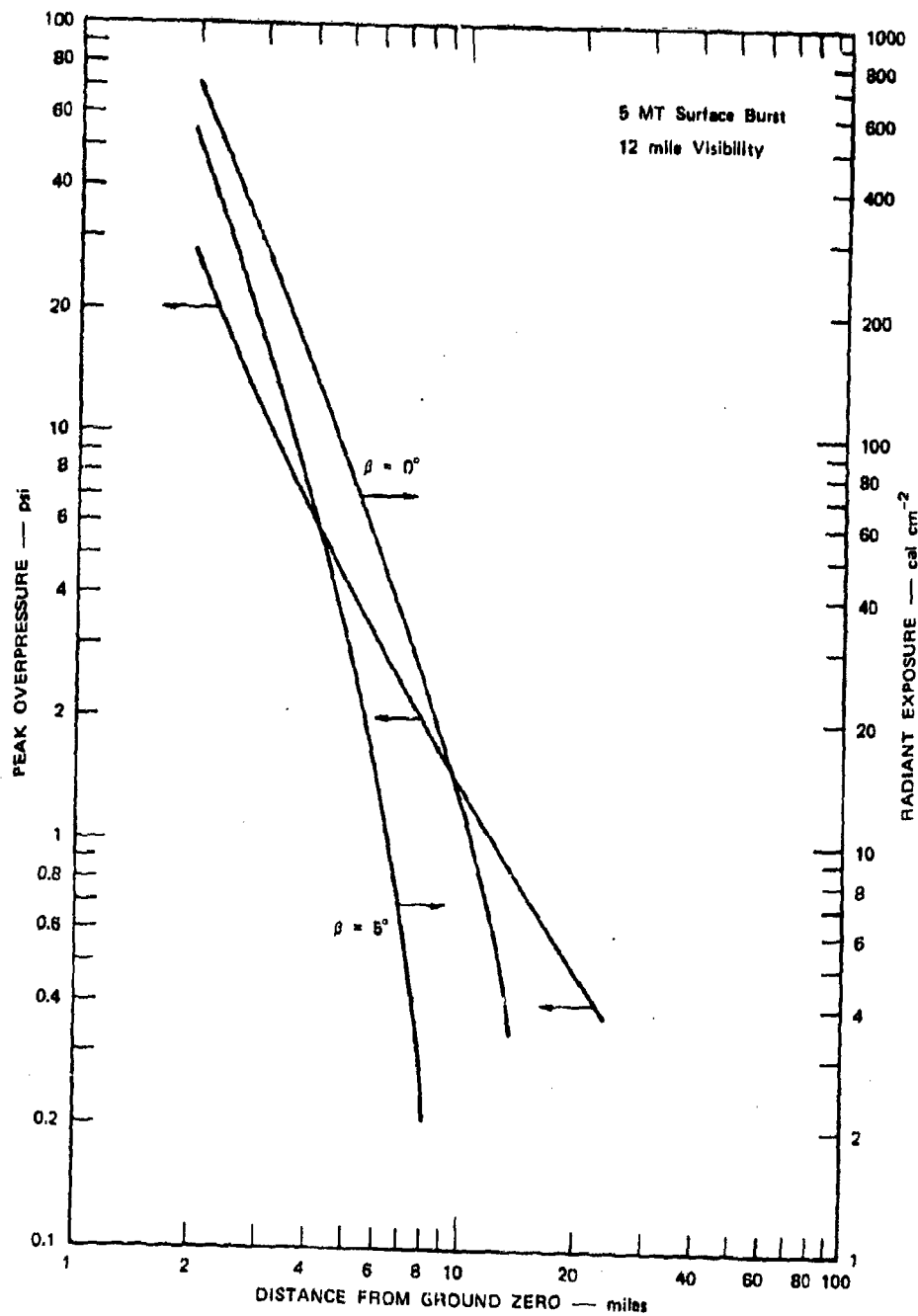
The second mechanism for reduction in radiant exposure is obscuration. The walls of the room, adjacent buildings, nearby trees, and opaque window coverings can partially or completely obscure the fireball from the view of ignitable contents of the room. This problem can only be treated in a probabilistic sense, but its effect is clearly a substantial reduction in the number of ignitable contents per room exposed to the requisite thermal load. More distant buildings and other opaque objects may also obscure a part or all of the fireball, but it is convenient to treat this problem differently, i e., as an "artificial horizon" which is more a property of the target area than it is a characteristic peculiar to an individual building and its immediate locale. Artificial horizons 5 to 8 degrees above the natural horizon appear to be common to urban areas. Windows in upper stories of tall buildings will be much less affected by the artificial horizon than will windows near the ground.

In a recent review of the subject of the role of fire in nuclear warfare, Martin³ shows that the incendiary reach (neglecting blast effects) can be identified with the distances from the burst point at which exterior radiant exposure levels approximate inflection point radiant exposures in cumulative mean-number functions for interior fuel inventories. In other words, this represents the point at which the average number of fuel items per room that will be ignited, if exposed, increases rapidly for only slight increases in the radiant exposure (e.g., the mean number roughly doubles for only a 10% increase in the radiant exposure level). For most situations involving megaton explosion yields, the inflection-point radiant exposure appears to vary only a little and has values in the range of about $20 \text{ to } 30 \text{ cal cm}^{-2} \text{ sec}^{-1}$.

For damage assessment purposes, it is convenient to relate incendiary reach of nuclear explosions to peak overpressure values for the blast wave originating from the same explosion. Figures B-1 and B-2 give free-field (i.e., unobscured) radiant exposures for 5 MT-yield surface and low air bursts on a clear day in relation to specified peak blast overpressures. The effect of a 5-degree artificial horizon is also shown for the surface burst.

For situations involving clear atmospheres (approximating 12 mile visibility), the incendiary reach for megaton-yield explosions; that is, distances to which 20 to 30 cal cm⁻² sec⁻¹ radiant exposures occur, will correspond to about 2 to 3 psi overpressures from airbursts and to roughly 2 psi overpressures from surface bursts when no artificial horizon intervenes or about 3 to 4 psi when the artificial horizon averages a 5 degree inclination over the true horizon. For less clear atmospheres the corresponding blast overpressures will be higher. Thus fires will not usually present a serious problem unless overpressures exceed 2 to 5 psi; that is, in built-up areas, fires will occur in, at most, two or three out of every hundred buildings at 2 psi due mainly to blast effects. Primary fires will occur, initially, in a third to a half of the structures experiencing 5 and more psi blast overpressures. This could lead to fire-storm conditions in heavily built-up areas if, but only if, the initial fires survive the subsequent blast wave.

Within a relatively short time (e.g., a 1/4 to 1/2 hour) following the detonation, if fire-suppression efforts are either not attempted or not effective, destructive fires will be well developed within many of the structures left standing. Areas of high building density suffering a high initial fire incidence have the potential of becoming fire storm areas, possibly within the first half hour after attack. In areas of high fire spread potential, mass fires may develop within the first hour or two and spread uncontrollably for many hours, possibly days, even though the initial fire incidence was light. In areas of low fire spread



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FIGURE B-1 COMPARATIVE LEVELS OF THERMAL RADIATION EXPOSURES AND BLAST OVERPRESSURES FOR A 5-MEGATON SURFACE BURST

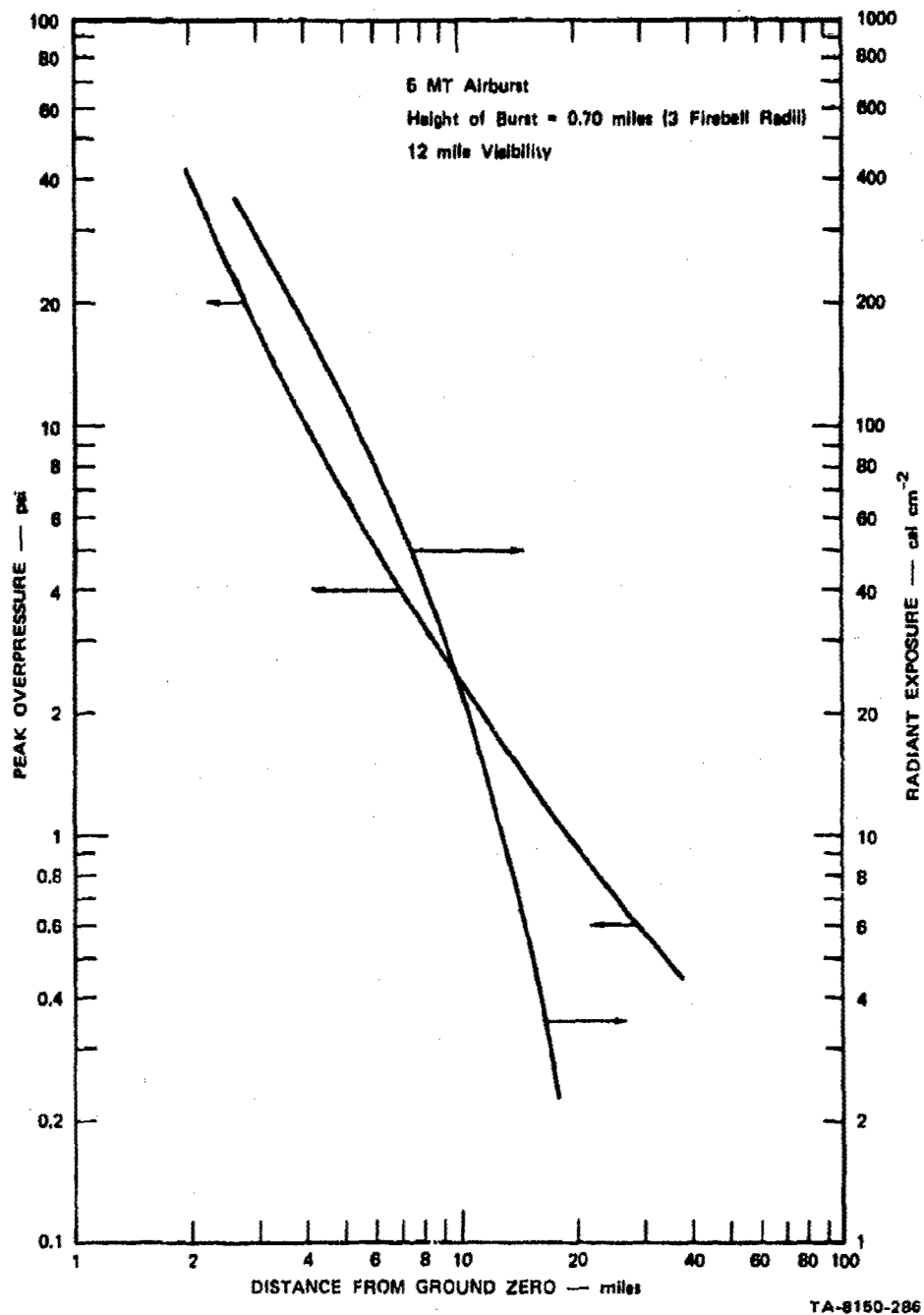


FIGURE B-2 COMPARATIVE LEVELS OF THERMAL RADIATION EXPOSURES AND BLAST OVERPRESSURES FOR A 5-MEGATON AIRBURST

potential, fires will typically spread slowly and be limited to within the block of origin or, at most, several blocks from that point, and will soon burn themselves out except under windy conditions when they may spread through the agency of firebrands for long distances in the downwind direction.

Self-help firefighting activities are tremendously important in the period between fire initiation and the time when they have grown to the point of flashover. After flashover, professional firefighting will be required, but the fire services will not be able to deal with the whole problem, and the only hope for fire control lies in a first-aid type response by building occupants. The time available for this depends very much on what materials are ignited, how many persist in burning, and whether they are in flames or just smoldering. It can range from less than 15 minutes, for cases where lots of active flaming results from the explosion, to an hour or more, when only smoldering fires result.

But what of the effects of blast on these fires? More than two decades ago, Traumontini and Dahl⁴ reported evidence that incipient fire in kindling fuels was extinguished by low peak overpressures. Their results were nearly forgotten until the subject was raised again in 1969 when further experiments confirmed their general conclusions but failed to substantiate the results in detail.

In all experiments reported to date, the blast-wave simulations have been inadequate to permit quantitative assessment of most practical situations. The fundamental weakness in simulation techniques to date is their lack of independent variability of peak overpressure, positive-phase duration, and flow behind the shock front. Such variability, if available, would allow systematic study of fire extinguishing mechanisms and their dependence on pertinent aerodynamic conditions that can vary so widely in an urban target.

In a recent series of tests,⁵ using the best simulation available at the time (i.e., peak overpressures variable up to about 8 psi, but of limited positive-phase duration and no independent control of flow) flaming combustion was extinguished by overpressures greater than 2.5 psi. Although smoldering combustion survived all overpressures applied, the additional time for self-help fire suppression provided by the extinguishment of flames offers considerable reason for optimism about the fire effects of nuclear attack.

A note of caution: results of shockwave extinguishment under experimental conditions in shocktubes have not been duplicated in the field. In fact, there is some contradictory evidence offering the disquieting possibility that blast-wave blowout is due to a phenomenon associated with, and peculiar to, the pressure discontinuities in idealized shockwaves. The whole subject is unfortunately based at present on very few observations and even less quantitative data.

High-speed motion pictures taken during tests in the URS shock tunnel suggest that shearless displacement of the flames off the ignited item in the wake of the shock is the mechanism responsible for extinguishment. However, subsequent tests in the field² in which liquid fuel beds were subjected to blast overpressures from high explosive did not exhibit this shearless displacement and, moreover, these fires survived all peak overpressures to which they were subjected from about 1 to 5 psi.

Thus, we do not know whether the shock front or the blast wind is the important factor in fire extinguishment, and the question of the importance of flow, pressure-flow-history, and positive phase-duration remains unanswered. To properly sort out the mechanisms of extinguishment and their dependence on blast-wave parameters, further research is critically needed. There are some highly significant implications to national defense involved here, and a high enough priority should be given to these problems to warrant adequate government funding of research programs to fill the

existing technical void and to resolve the remaining questions about extinguishment of fires by blast waves in urban targets.

REFERENCES

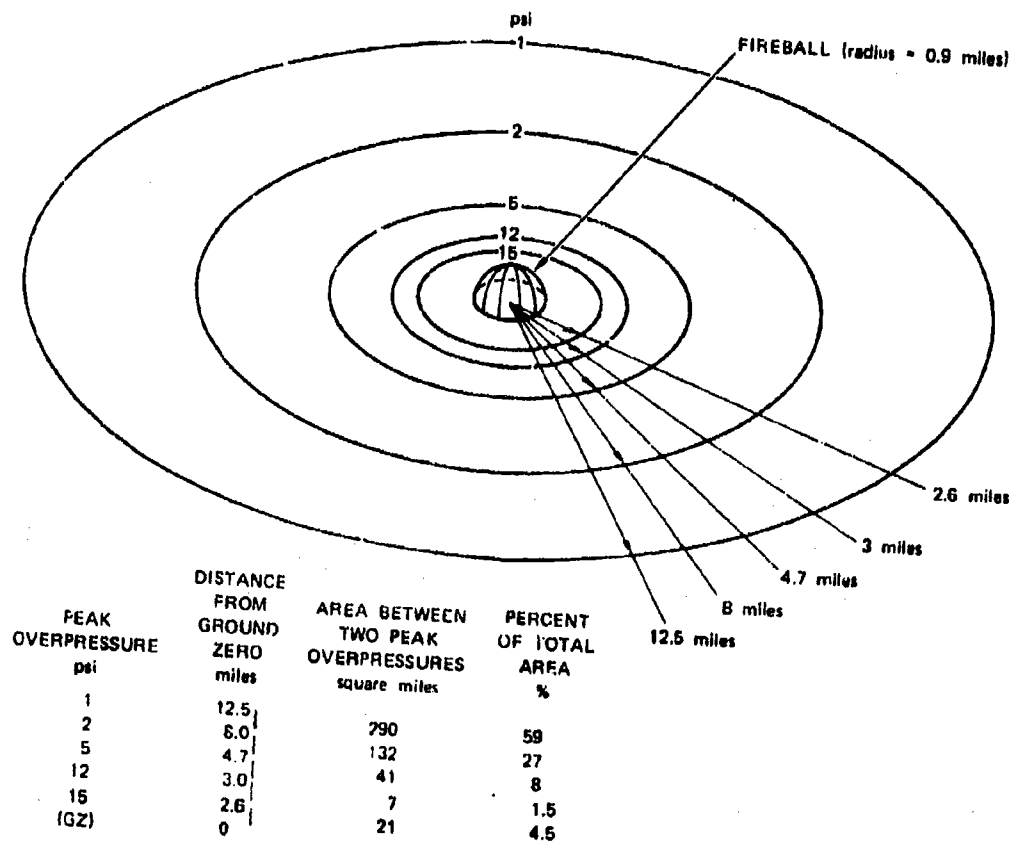
1. J. McAuliffe and K. Moll, "Secondary Ignitions in Nuclear Attack," OCD Work Unit 2534A, Stanford Research Institute Menlo Park, California (July 1965).
2. S. J. Wiersma and S. B. Martin, "Evaluation of the Nuclear Fire Threat to Urban Areas," DCPA Work Unit 2561A, Annual Report, Project PYU 8150, Stanford Research Institute, Menlo Park, California (September 1973).
3. S. Martin, "The Role of Fire in Nuclear Warfare," DNA 2692F, URS Research Company, 155 Bovet Rd., San Mateo, California 94402, Final Report (August 1974).
4. V. N. Traumontini and P. R. Dahl, "Forest Fuels Blast Studies Interim Report," Report No. 53-15, University of California, Los Angeles, California (June 1953).
5. T. Goodale, "Effects of Air Blast on Urban Fires," OCD Work Unit 2534I, Final Report, URS Research Corporation, Burlingame, California (December 1970).

DESCRIPTION OF DAMAGED URBAN AREAS IN THE EARLY TRANSATTACK PERIOD

More than 95 percent of the area subjected to the direct damaging effects of a megaton explosion lies between the 1 and 15 psi overpressure contours, as illustrated in Figure 7, and probably close to 99 percent (or more) of the survivors of the direct effects (those inside the 1 psi contour) are within this ring. Therefore, the principal concern about direct effects and their impact on emergency operations and the continued survival of the victims of direct attack centers on this area lying between the 1 and 15 psi overpressure contours. Interestingly, a very large part of this area (roughly 90 percent of it) experiences less than 5 psi, a fact of considerable significance to that part of the population that must seek shelter in residential areas. In the area between 5 and 15 psi, prospects for surviving the blast effects are fair to good, depending upon how well the population has made use of the best available shelter spaces. Nevertheless, they, along with the other survivors of the direct effects area, are endangered by the fires resulting from blast damage and by those which, after being started by the thermal radiation, persist and survive the extinguishing effects of the blast wave. The planning of emergency actions in this directly affected region of an urban area must of necessity be based on the best possible assessment of the damaged environment and the residual fire risks that the current state of the art permits. In the following material, such an assessment is offered.

A. Approach

An illustrative yet quantitative example is used. Residential and commercial land-use situations are represented since these comprise the largest portion of an urban complex. A 5-megaton surface burst and a



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FIGURE 7 AREA AFFECTED BY A 5-MEGATON SURFACE BURST

5-megaton low airburst have been chosen as representative of present-day strategic attack scenarios. Minor variations would result from the choice of other yields in the megaton range and for other airburst situations. These minor differences do not affect the overall uncertainty of incendiary outcome that results from our present inadequate understanding concerning the mechanisms and consequences of blast extinguishment.

Atmospheric attenuation of thermal radiation has been defined by the choice of a 12-mile visibility. This choice emphasizes thermal radiation effects since urban atmospheres rarely are that clear. For surface bursts, however, differences in atmospheric transmission tend to be overpowered by obscuring effects of the artificial horizon and nearby buildings and trees. Nevertheless, the reader of the following material should bear in mind that the 12-mile visibility favors primary ignitions.

One-story wood frame and load-bearing brick structures have been taken as typical of 1- and 2-family residential area construction. A building density* of 0.2 was taken as representative of such areas.

For the built-up commercial situations, several types of construction and a variety of building heights and densities were selected as representative. The major structural categories were:

- Frame--intended to cover both steel and reinforced concrete frame structures having relatively weak wall panels and interior partitions.
- Masonry--representing the general class of structures in which floors are borne by masonry walls. These are of two kinds; (1) weak walled, and (2) monumental or strong walled. The differences are important both from the standpoint of survival and of debris distribution.

*Defined as the fraction of total land area covered by buildings.

Two framed-building situations have been considered: (1) 5- to 10-story buildings in an area where the building density averages 0.4, and (2) 10- to 20-story buildings in a 0.6 building-density area. Situations involving weak-walled masonry load-bearing buildings have been represented by a large (14,000 sq. foot plan area), 6-story structure in an area where building density averages 0.5 (e.g., a large department store in an older downtown area). Two masonry-strong-wall situations are considered: (1) in an area of moderate (0.5) building density, a large monumental building of 12 stories height (e.g., a Federal office building), and (2) a similar building but much larger and taller in an area of high (0.7) building density.

Descriptions of blast damage to these structures are a consensus of several sources.^{1,10-16} Survival probabilities are drawn from analyses conducted by Longinow.¹⁷

In the estimates of direct-effect survival probabilities, four different basement shelter situations have been considered in addition to the different buildings. All residential basements are treated as a single structural case, the typical below grade (or mostly below grade) basement with concrete walls covered with a wood-joist floor. Survival is thought to be substantially more likely whenever the occupants of the basements assume prone positions along the concrete walls, and the estimates reflect this belief.

In the built-up commercial areas, three basement floor covering systems are considered:

- (1) Concrete slab-steel beam
- (2) Concrete slab-concrete beam
- (3) Flat plate

The first of these was chosen because it is the most common type of construction and because it provides perhaps the best available basement protection. Nearly a quarter of the NFSS basement spaces are in this category.

Of the 36 cases that have been analyzed, nine were of this type, providing a fairly good level of confidence in the representativeness of the survival estimates.

The concrete slab-concrete beam system was chosen because it is the second most common category. The flat plate, although it represents only about 6% of the NFSS basement spaces, is the third most common category and it probably typifies the weakest floor covering system for commercial basements.

Estimates of fire probability are derived from calculations using the SRI BLASTFIRE computer program that was described and reproduced in the previous report.¹

The principal new contribution in this assessment is derived from the debris analysis described in the previous section. Data resulting from the sensitivity analysis were correlated to predict the characteristics of distribution of the debris (both building components and contents) created and/or translated by the blast wave. If one thinks of the debris ejected from a building as being characterized by certain class-average properties (i.e., mean values of the drag coefficient, thickness, cross-sectional area, density, etc.) one anticipates that the debris from an isolated building will come to rest in a pattern distributed about some mean downstream distance, call it the mean free-field displacement. This mean distance will be a function of the class-average properties of the separate debris constituents, of the dimensions of the building, and of the drag-force characteristics of the blast wave. The sensitivity analysis shows that, contrary to expectation, the displacement of a debris fragment is not strongly dependent on the building height. Accordingly, we anticipate that a successful correlation will be one in which the principal independent variables will be those concerning the dynamic pressure pulse and the drag properties of the debris elements.

In its simplest terms, the drag force acting on a particle of area A is $F(t) = C_d A q(t)$; where C_d is the drag coefficient and $q(t)$ is the dynamic pressure. In the absence of any other forces, the particle will accelerate in the direction of the flow as prescribed by the equation

$$a(t) = \frac{F(t)}{m} = \frac{C_d A}{m} q(t)$$

where the symbol m stands for the mass of the fragment. As long as the velocity of the debris fragment remains small compared with the air particles in the flow field, the symbol $q(t)$ may be identified with the dynamic pressure pulse as measured at a fixed location.

After a time t , during which the debris fragment has been exposed to the drag influence of the dynamic pressure pulse $q(t)$, the velocity of the fragment will attain a value

$$v(t) = \frac{C_d A}{m} \int_0^t q(\tau) d\tau$$

In the low shock-strength region of a nuclear explosion,

$$q(t) = q_0 \left(1 - \frac{t}{t_+}\right)^2 e^{-2t/t_+}$$

where q_0 is the peak pressure (at $t = 0$) and t_+ is the duration of the positive phase. Therefore,

$$v(t) = \frac{C_d A}{m} \int_0^t q_0 \left(1 - \frac{\tau}{t_+}\right)^2 e^{-2\tau/t_+} d\tau$$

Evaluation of the integral gives:

$$v(t) = \frac{C_d A t_+}{m} q_0 \left[1/4 - 1/4 e^{-2t/t_+} + 1/2 \frac{t}{t_+} e^{-2t/t_+} - 1/2 \left(\frac{t}{t_+}\right)^2 e^{-2t/t_+} \right]$$

Accordingly, the distance to which the fragment is displaced during the positive phase is given by,

$$d(t_+) = \int_0^{t_+} v(t) dt = \frac{C_d A}{m} q_0 t_+^2 \left[1/8 + 3/8 e^{-2} \right]$$

Thus, we might anticipate the following relationship to give the mean displacement of debris having class-average properties \bar{C}_d and (\bar{A}/m)

$$\bar{d} = f(h) \cdot \bar{q}_0 t_+^2 \bar{C}_d \bar{A}/m$$

but since $\rho = m/\bar{A}L$,

$$\bar{d} = f(h) \cdot \bar{q}_0 t_+^2 \bar{C}_d / (\bar{\rho} L)$$

where $f(h)$ is some weak function of the building height h and $\bar{\rho} L$ is the mean value of fragment mass per unit area.

Data resulting from the debris calculations were plotted first as the product $\bar{d}(\bar{\rho} L)$ versus $q_0 t_+^2$ with initial height as a parameter. The correlation was only fair; the most obvious failing was the lack of inverse proportionality between \bar{d} and $\bar{\rho} L$. Through a process of trial and error a usable correlation was achieved by plotting $\bar{d} (\bar{\rho} L)^{3/4}$ against peak overpressure. This is shown as Figure 8. Although the correlation was not entirely satisfactory, it did provide the necessary trends from which predictions of debris displacement and depths could be derived.

The procedure was based on the presumption that the distribution of debris could be adequately characterized in terms of the three wall-material densities used in the sensitivity analysis (with a common thickness of six inches) and two categories of contents as shown in URS 705-5,¹⁵ having values of mass-per-unit area approximating 1 and 10 lb_m/ft^2 (i.e., the lightest building debris roughly corresponds to the heavier category of contents), thereby reducing the number of categories to be considered to four. Accordingly, in situations where a substantial contribution to the total debris is made by building components, the mean displacement is taken to be the one calculated for the middle category wall-material density and the range corresponds to the difference between the displacements of the heavy and light components. In situations where building contents constitute the major portion of the debris, i.e., for blast overpressures that are below the typical collapse values, the distribution is estimated from the two property values for contents.

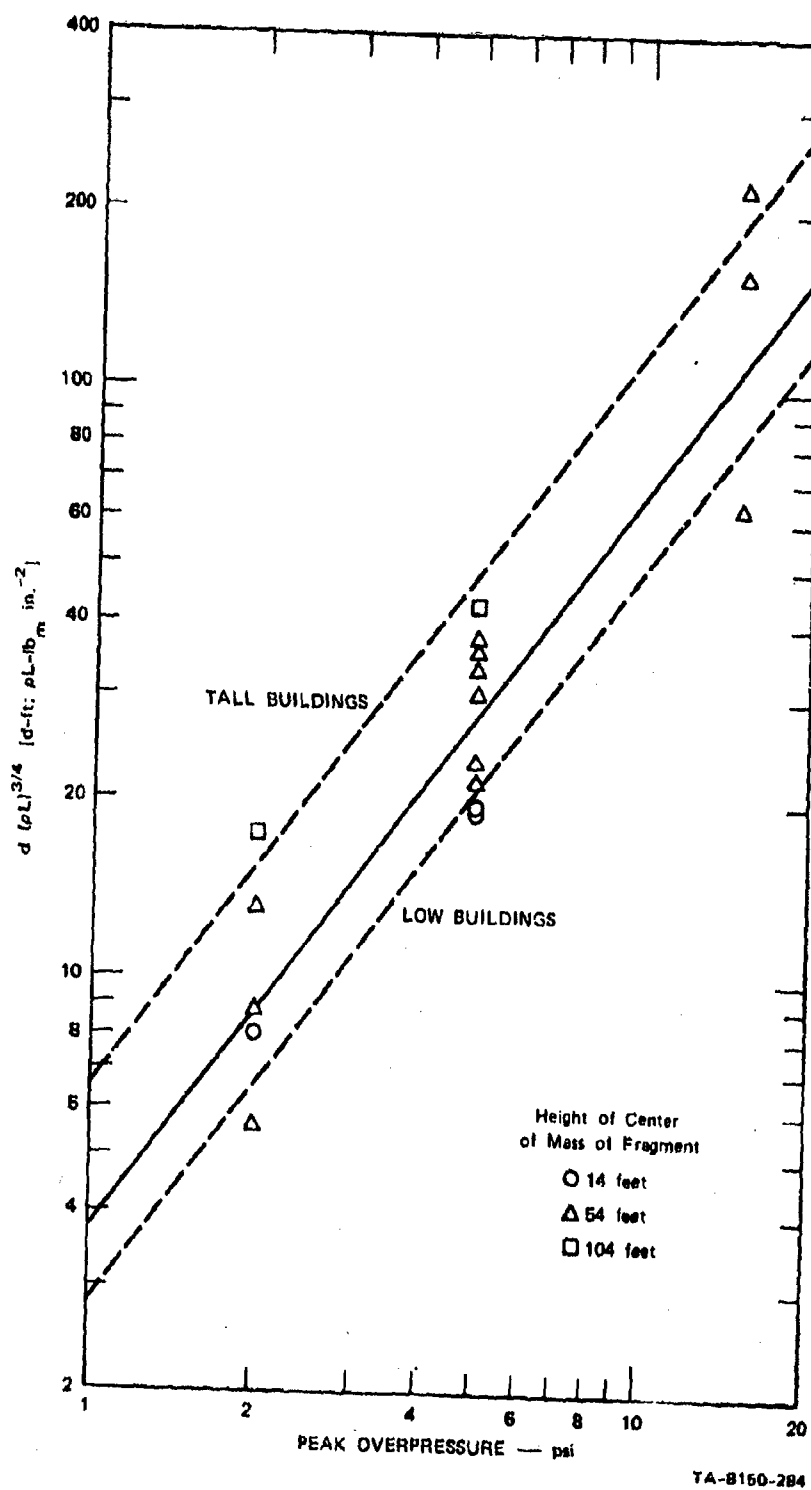


FIGURE 8 DEPENDENCE OF DEBRIS FRAGMENT DISPLACEMENT ON PARTICLE DENSITY, PEAK OVERPRESSURE, AND BUILDING HEIGHT

Finally, the fuel-to-nonfuel ratios for the debris have been estimated from material given in URS 651-4.¹⁶

B. Results

Table 2 summarizes the predictions of blast and fire effects at overpressures of 15, 12, 10, 5, 2, and 1 psi. As previously noted, the incendiary outcome is critically dependent on blast-fire interactions. In the 1 to 5 psi region, even though substantial debris depths may result in the built-up commercial areas, there are significant open areas.

A striking result of this study is the uniform coverage of debris. Under most circumstances, debris covers all the available space, leaving no open areas free of debris. It had been expected that there would be open areas throughout the regions of the target experiencing low overpressures, but the finding was that under the majority of circumstances debris is dispersed over all of the available area, leaving few debris-free areas.

Descriptions of the two land-use areas as they are predicted to respond to two ranges of overpressure, 2 to 5 psi and 5 to 15 psi, follow:

1. Residential Areas--2 to 5 psi Region

In this overpressure region of residential land-use areas, most of the transition from standing structures to collapsed structures would be found; i.e., at 2 psi there would be few cases of collapse, at 5 psi nearly all wood frame and load-bearing masonry buildings would be totally collapsed. In the higher overpressure part of this region, those structures left standing will be specially reinforced buildings and some of the more substantial masonry buildings (e.g., schools, libraries, fire stations). When these more substantially built structures do collapse, a large part of their heavy debris remains on site. But in all cases, the structural debris in this region will rarely be dispersed to cover more than about twice the building plan area. That is, it will ordinarily cover much

Table 2

BLAST-FIRE EFFECTS PREDICTIONS

Peak Overpressure psi	Distance from Ground Zero miles	Fraction of Object Effective Area Inside Overpressure Contour	Time of Blast Arrival sec	Urban Land Use	Structural Type	Building Density (7)	Typical Plan Area (A) ft ²	Typical Height (B) ft	Radiant Exposure (Q) cal/cm ²	Probability of Significant Damage from Blast (11)	Radiant Exposure Following Blast Arrival cal/cm ²
15	2.45 ^a (3.21)	5 ^a (3)	5.3 ^a (12)	Residential	Wood frame	0.2	3,500 ^b	20	247 ^a (226.4)	10.7 ^a (11)	126 ^a (177)
					Load-bearing masonry	0.7	4,000	20			
				Build-up Commercial	Frame	0.4	12,500	80		11.8 ^a (12.2)	0.437 ^a (0.465)
					Masonry W.W.	0.5	14,000	75			
					Masonry S.W.	0.5	15,000	150			
						0.7	32,000	200			
12	2.37 ^a (2.74)	8 ^a (4)	6.15 ^a (12.7)	Build-up Commercial	Frame	0.4	12,500	80	181.5 ^a (207)	8.6 ^a (9.9)	0.432 ^a (0.465)
					Load-bearing masonry	0.6	20,000	160			
					Masonry W.W.	0.5	14,000	70			
					Masonry S.W.	0.5	15,000	150			
						0.7	32,000	200			
10	2.36 ^a (4.14)	7 ^a (5)	7.7 ^a (15.4)	Residential	Wood frame	0.2	3,500	20	128.9 ^a (171.4)	6.0 ^a (7.4)	0.204 ^a (0.281)
				Build-up Commercial	Frame	0.4	12,500	80		6.6 ^a (8.2)	0.3703 ^a (0.464)
					Load-bearing masonry	0.6	20,000	160			
					Masonry W.W.	0.5	14,000	70			
					Masonry S.W.	0.5	15,000	150			
						0.7	32,000	200			

(a) For each overpressure listed, the first number is given for a 3-ft surface burst. The number in parentheses is for a 5-ft air burst with a height of burst of 3 ft (small radii) or 2.1 sites.

(b) The area used is an average of 1- and 2-family dwellings, including garages.

(c) Q is the inflection-point value of radiant exposure in the mean number distribution of ignitable debris.

(d) In the survival probability column the parenthesized numbers are for noncharring walls.

Table 2 (Continued)
BLAST-FIRE EFFECTS PREDICTIONS

Peak Overpressure	Distance from Ground Zero	Fraction of Direct-Effects Area Inside Overpressure Contour	Time of Blast Arrival	Urban Land Use	Structural Type	Building Density (f)	Typical Plan Area (A)	Typical Height (H)	Radiant Exposure (q)	D/D ₀	Probability of Significant Room Fire (Without Blast Effects)	Reliable Blast Exposure Following Blast Arrival	Survival Probability (%)				Debris Description										
													(%)				Description of Blast Damage	Above Ground	Below Ground	Prone	Mean Displacement (Free Field)	Displacement Range (Free Field)	Area Covered (A) (Free Field)	Area Covered (A) (Free Field)	Fraction of Plan Area Covered (A) (Free Field)	Area Covered (A) (Free Field)	Fuel/Mineral Ratio
5	4.72 (16.2)	14 (10)	13.7 (22.7)	Residential	Wood Frame	0.2	3,500	21	41.8 (21.3)	1.8 (3.1)	0.00286 (0.00063)	10 (11)	70	80	70	>90	80	70	40	8.4	2.4	0.5	1.7	2.4	11		
					Load-bearing masonry	0.2	4,000	20					80	100	80	40	40	40	40	8.9	2.2	0.65	1.6	~ 1	1		
				Build-up Commercial	Frame	0.4	12,500	40		2.0 (3.4)	0.01102 (0.037)		150	150	150	40	40	40	40	22.1	1.8	0.7	4.9	4.9	1		
					Frame	0.6	30,000	160					300	300	300	100	100	100	100	63.7	2.1	1.3	10.6	1.5	1		
					Masonry, S.F.	0.5	14,000	70					90	90	90	40	40	40	40	23.4	1.7	0.8	6.2	2.1	1		
					Masonry, S.F.	0.5	15,000	350					300	300	300	100	100	100	100	45	3	1.5	2.8	2.5	1		
						0.7	32,000	200					300	300	300	100	100	100	100	65.8	2	1.4	7	1.5	1		
2	8.01 (11.3)	41 (26)	27.4 (44)	Residential	Wood Frame	0.2	3,500	20	2.6 (13.4)	0.11 (.34)	0.00000 (0.00028)	0.3 (0.37)	200	200	200	40	40	40	40	25.4	19.1	2	0.2	2.2	1		
					Load-bearing masonry	0.2	4,000	20					200	200	200	425	38	5	5	38	9.5	1.9	8.2	2.2	1		
				Build-up Commercial	Frame	0.4	12,500	80		.12 (.44)	0.00000 (0.0015)		250	250	250	549	90.0	7.2	2.9	90.0	7.2	2.9	1.6	1.5	1		
						0.6	30,000	160					400	400	400	920	920	920	920	7.5	4.5	4.8	4.8	1.5	1		
					Masonry, S.F.	0.5	14,000	70					250	250	250	540	93.8	6.7	2.4	93.8	6.7	2.4	1.8	1.5	1		
					Masonry, S.F.	0.5	15,000	350					400	400	400	918	10.6	5.2	10.6	10.6	5.2	3.8	3.5	1			
						0.7	32,000	200					400	400	400	924	7.3	5.1	7.3	7.3	5.1	7	1.5	1			
1	12.5 (19.3)	100 (100)	46 (72)	Residential	Wood Frame	0.2	3,500	20	0.6 (1.8)	0 (0.08)	0.00000 (0.00000)	Regl	250	250	250	549	90.0	7.2	2.9	90.0	7.2	2.9	1.6	1.5	1		
					Load-bearing masonry	0.2	4,000	20					250	250	250	549	90.0	7.2	2.9	90.0	7.2	2.9	1.6	1.5	1		

less than the total area, often less than half of it even in areas of high building density. (High for residential areas, that is).

On the other hand, the light contents of the buildings, either ejected through windows and doors or ejected during collapse, cover a large part of the open spaces between buildings and their structural debris piles. Thus, we would expect to see large discrete piles of building debris with extensive open spaces separating them, over which there would be a thin, heterogeneous, and substantially discontinuous (scattered and spotty?) litter of paper, fabrics, cushions, light chairs and tables, lightly attached panels, pillows and mattresses, etc.

There would be few, if any, primary fires at 2 psi--probably none in the debris. Airbursts could cause some fires but they would probably be few in number compared with secondary fires (i.e., only about 1 or 2 fires in a thousand exposed buildings). This primary fire incidence increases rapidly with increasing peak overpressures. At 5 psi, for example, a surface burst would cause roughly the same frequency of primary and secondary fires (i.e., 1 or 2 in a hundred structures), while airbursts would perhaps cause one or more fires in every structure. Whether (and how many of) these incipient primary fires survive the subsequent blast wave and the displacement of the debris it generates is quite uncertain at present. Flames will probably be blown out in most circumstances, but smoldering combustion will persist and can rekindle flaming combustion later. With the possible exception of the effects of low airbursts in the higher overpressure extreme of this region, initial fire density would be typically low. Possibly, an average of one debris fire out of 100 to 500 structures exposed to direct effects is representative of this 2 to 5 psi region of a residential target area.

Given such low levels of fire incidence and the largely discontinuous nature of the debris, the fires that do occur will usually burn out and not spread to other debris piles. The rare instances of merging will only tend to limit the fire rather than cause it to intensify, because it will have no more fuel to consume. Spread characteristics within a debris pile will be determined principally by the ambient wind.

Basement spaces and structures still standing will provide fire-safe refuge in most instances. With proper precautions, a very high level of survival can result. Self-help firefighting can be important in the relatively infrequent circumstances where fires do start in the occupied building. Occupants have 10, perhaps 20, minutes to find sustained fires and to either extinguish them or eject the burning items from the building (making sure that a path of combustible debris between the item and the building is not left to allow the fire to return). Wherever special below-ground shelter is provided, air vents should be 100 feet or more from building foundations to minimize the chances of their being covered with debris. Even with this precaution, it would be advisable, following the passage of the blast wave, to check whether the vent is in the open. If not, it may be necessary for a few shelter occupants to risk exposure to clear debris away from the vent and/or to provide for closing off the vent during any periods when fires are burning in the immediate locality. As previously noted, a simple indicator of combustion product hazards is air temperature. A provision for monitoring the temperature of the air at the vent intake would be a very useful guide for deciding when to close off the vent and for how long.

2. Residential Areas--5 to 15 psi Region

As the incident overpressure increases from 5 to 10 psi, mean debris displacement more than doubles, so that for situations in which 5 psi overpressures create discrete debris piles separated by areas as

large or larger containing only a light building-contents litter, the same situations at 10 psi and higher overpressures result in reasonably uniform debris depth covering most of the available area. Exceptions would be large open areas such as parks, schoolgrounds, and large undeveloped areas.

Debris depths in the 10 to 15 psi portion of this region will be substantially less than at 5 psi because the same amount of debris (that is, the total quantity provided by both the building and its contents) is spread over a larger area. Once the total area is covered, however, no further decrease is possible. This limiting depth of fairly uniform coverage for a typical suburban area is in the range of 1/2 to 1 foot thickness. Tree foliage can add substantially, increasing both the depth and the fuel content.

Prior to blast arrival, the frequency (incidence) of those primary fires that would surely destroy the structure in which they occur if left unperturbed by blast would be quite high except for surface burst conditions in the lower part of the overpressure range. Although the incidence is very low at 5 psi for a surface burst (2 orders of magnitude less than for an airburst), at 10 psi it is quite large. Assuming that an average of 5 rooms are exposed in each residential building, at 10 psi the probability that one or more significant fires will occur per building is about 2/3 for a surface burst and over 9/10 for a low airburst. In both cases this probability appears to approach the same limit of about 0.8 for overpressures exceeding 10 psi.

Again, as in the low-overpressure-region cases, we are uncertain of the outcome following blast wave interaction and structural collapse; but when all factors are considered, it appears that fire incidence will be quite high, particularly in the upper end of the overpressure range. One fact that cannot be ignored is ignition of debris after it is

formed. At overpressures of 10 psi and more, there is still sufficient thermal exposure left (and delivered at still effective levels of radiant power) after the arrival of the blast wave to ignite the debris it forms. It should not be concluded from this statement, however, that fires are assured. The radiation will be attenuated by dust clouds and the actual exposure of the debris is quite uncertain. All-in-all, the prospects for low fire incidence in this region are not good.

Given a continuous field of combustible debris and a high frequency (density) of fire starts, it appears that fire spread cannot play a dominant (or even a very important) role in the fire picture except perhaps in the very early period while the numerous small fires are in the process of merging. Rather, since we anticipate a relatively uniform debris field burning all at once, the hazard is determined largely by burning rates and CO, CO₂ yields.

The fuel loadings of 1.5 to 3 pounds per square foot that will be found in the residential zones in this 5 to 15 psi region will have maximum burning rates ranging from 0.1 to 0.2 pound per square foot per minute. The burning rate will not be substantially affected by the nonfuel loadings that are typical of residential area debris. The CO yield will be about 5 percent of the burning rate in the same units. Air vents to the below-ground shelters will need to be closed for that period of time when the debris is burning in the immediate vicinity of the intake. The hazard period will be on the order of 30 minutes long. As stated before, the air temperature of the vent intake is an indicator of the carbon monoxide hazard and could be used to determine when the vent intake could be reopened.

3. Built-up Commercial--2 to 5 psi Region

This is the region of light-to-moderate structural damage to these structures that characterize built-up commercial areas of an urban

target. Outright collapse is not expected to occur except in some wood-frame buildings and buildings of relatively weak-walled masonry construction. However, curtain walls in steel and concrete frame buildings, along with interior partitions in general, are apt to fail, and in some situations, these can be so thoroughly swept out of the framing sections by the pressure differentials (particularly in non-arching wall construction) that only the frame is left in place. (Note the 47% survival probability at 5 psi for frame buildings with nonarching wall construction). Survival of initial effects by above-grade shelter occupants depends on whether they have taken a suitably protective prone position at the time the blast wave arrives, especially in frame buildings with nonarching walls, but the chances of survival in weak-walled masonry buildings are negligibly small no matter what precautions have been taken. The prognosis for survival may be increased by seeking shelter below ground. However, basements covered by floors of flat-plate construction are to be avoided as they provide less protection than above-ground spaces, except for those in weak-walled masonry buildings.

Debris in this region tends to cover most of the available space, leaving relatively few open areas. In the lower overpressure part of this region, debris is composed mainly of building contents. Nevertheless, it is of sufficient volume to cover the available area to a considerable depth (typically 2 to 10 feet deep). Its composition is such that it exhibits a high fuel content.

In the higher overpressure range, interior partitions, roof sections, and other light structural components are ejected into the debris field. Debris depths are, on the average, greater than at the low overpressure end of the region but typically less than twice as deep.

In general, the fire incidence is somewhat higher than in the residential areas experiencing the same overpressures. In the commercial areas there is a strong gradient in initial (prior to blast arrival) fire density with distance. For surface bursts fires that occur at 2 psi will be mostly secondary fires. Airbursts will add an approximately equal number of primary fires in smaller buildings, but the magnitude will be one order higher in the big buildings where many more rooms are exposed to the full thermal radiation. At 5 psi, airbursts will cause primary fires in nearly all exposed buildings--surface bursts in perhaps one third.

Following the arrival of the blast wave, the situation becomes uncertain. Although fire incidence may be high--and this is especially true for low airbursts, but also true for both surface and airbursts in the upper end of the overpressure range--it is not at all clear whether most of the fires will be in the debris field or in the still-standing buildings. It may be conjectured that most of the fires in the low-overpressure part of the region will be in the structures, whereas in the high overpressure part they will be in the debris. Rates of fire spread will be important determinants of the threats to survival, at least in the lower range of overpressures where initial fires will be widely scattered.

In the low-overpressure part of the region where the fires are mostly in the still-standing buildings, self-help firefighting can be most important to increasing the level of survival. If the fires in many of the buildings are permitted to develop to full building fires and permitted to spread to the debris field, an almost certain mass fire situation will develop in this region. Then, even the sheltered people in the area will be critically threatened by the heat and combustion products of the fires.

In the higher overpressure part of this region, the chance of a mass fire situation is dependent on fire incidence in the debris and the rate of fire spread through the debris, which is highly dependent on ambient wind. The primary fire incidence is estimated to be one in every 30,000 to 100,000 square feet of debris or a mean distance between fires on the order of 300 feet. For ambient winds of greater than 7 mph, these incipient fires will become uncontrollable by self-help firefighting techniques in less than 20 minutes and will merge into one large mass fire in less than an hour. For very low ambient winds (less than 3 mph), the time required for the incipient fires to merge will probably be longer than the time for some debris areas to burn out.

4. Built-up Commercial--5 to 15 psi Region

This is the region where most of the structural collapse occurs in buildings that typify built-up commercial areas. Most weak-walled masonry buildings will have failed at 5 psi. Flatplate floor slabs (typical of many buildings constructed since 1950) over basement shelters fail in the 6 to 7 psi range. Survival probability above ground will be low even in the 5 to 10 psi part of the region except in buildings of monumental construction, but survival probability below ground can be high, depending heavily on the floor slab and support construction.

Debris would be expected to cover most of the area to depths ranging from about 4 feet at 5 to 6 psi to 20 feet in heavily built-up areas experiencing 12 to 15 psi and more. Although the fuel content of the debris can be as low as 1/3 of the total, in many situations the fuel-to-nonfuel ratio is unity or greater.

Fire incidence is expected to be high over much of this region. Virtually every structure would have several significant fires before blast arrival that would quickly develop into a mass fire if left undisturbed.

The blast wave may drastically change this situation by blowing out some fires and smothering others under debris, but many will probably survive and more will result from exposure of combustible debris to the still high radiant exposure levels. Here again the uncertainties due to dust obscuration are quite large.

As in the counterpart residential case, fire spread will not be as important a factor as the burning rates of the fully involved debris fires. Burn durations will be measured in hours. Prospects for continued survival are bleak even in well protected subgrade structures because of the problems of providing ventilation through the deep fields of burning debris. Large open spaces (e.g., very large parks) are perhaps the only reliable refuge.

REFERENCES

1. S. J. Wiersma and S. B. Martin, "Evaluation of the Nuclear Fire Threat to Urban Areas," DCPA Work Unit 2561A, Annual Report, Project PYU 8150, Stanford Research Institute, Menlo Park, California (September 1973).
2. V. N. Traumontini and P. R. Dahl, "Forest Fuels Blast Studies Interim Report," Report No. 53-15, University of California, Los Angeles, California (June 1953).
3. T. Goodale, "Effects of Air Blast on Urban Fires," OCD Work Unit 25341, Final Report, URS Research Company, Burlingame, California (December 1970).
4. J. H. Boyes, M. P. Kennedy, and C. Wilton, "Development of a Long Duration Flow Facility for Studies of Blast-Fire Interaction," URS 7239-6, URS Research Company, San Mateo, California (December 1974).
5. S. J. Wiersma, "Characteristics of Fires in Structural Debris," Final Report to DCPA, Naval Surface Weapons Center, White Oak, Maryland (January 27, 1975).
6. S. J. Wiersma, "Measurements of the Dynamics of Structural Fires," DCPA Work Unit 2561A, Annual Report, Project PYU 8150, Stanford Research Institute, Menlo Park, California (August 1972).
7. Louis E. Wise and Edwin C. John, Wood Chemistry, Reinhold Publishing Corporation, New York (1952).
8. C. M. Countryman, "Mass Fires and Fire Behavior," U. S. Forest Service Research Paper PSW-19, Berkeley, California (1964).
9. A. Longinow and G. Ojdovich, "Computer Program for Predicting the Safety of People in a Direct Effects Nuclear Weapon Environment," IIT Research Institute, Chicago, Illinois.
10. C. K. Wiehle, "All-Effects Shelter Survey System -- Summary of Dynamic Analysis of 25 NFSS Buildings," Technical Report for DCPA, Stanford Research Institute, Menlo Park, California (March 1973).

11. The Effects of Nuclear Weapons, 3rd Edition, Compiled and Edited by Samuel Glasstone and Philip J. Dolan, Published by the U.S. Government Printing Office, Washington, D.C. (1977).
12. Chapter 2, "What the Planner Needs to Know About Blast and Shock," DCPA Attack Environment Manual, Defense Civil Preparedness Agency, Washington, D. C. (June 1972).
13. C. K. Wiehle and J. L. Bockholt, "Existing-Structures Evaluation, Part V: Applications," OCD Work Unit 1154F, Final Report, Project 6300, Stanford Research Institute, Menlo Park, California (July 1971).
14. C. K. Wiehle and J. L. Bockholt, "Blast Response of Five NFSS Buildings," OCD Work Unit 1154I, Technical Report, Project 1219, Stanford Research Institute, Menlo Park, California (October 1971).
15. S. B. Martin, R. W. Ramstad, T. Goodale, and C. A. Start, "Effects of Air Blast on Urban Fire Response," URS 705-5, URS Research Company, Burlingame, California (May 1969).
16. J. Rotz, J. Edmunds, and K. Kaplan, "Formation of Debris from Buildings, and Their Contents by Blast and Fire Effects of Nuclear Weapons," URS 651-4, URS Systems Corporation, Burlingame, California (April 1966).
17. A. Longinow, "Survivability in a Direct Effects Environment (Analysis of 50 NFSS Buildings)", Final Report, Project J6311, IIT Research Institute, Chicago (July 1974).

Appendix B

DNA-Supported Program

at SRI in

EXTINCTION OF FIRE BY BLAST WAVES

(FY 1978)

Theoretical Background

Currently, there are three mechanistically distinct concepts that serve as bases for theoretical analysis of blast extinction and can provide hypotheses for experimental tests. However, their formal development as mathematical models of blast extinguishment is incomplete. Theoretical derivations have been limited primarily to conditions of steady laminar flow. Only one theory deals with the dynamics of shock waves, and even in that case, principals of steady-state boundary layers must be used to obtain numerical evaluation.

For present purposes, we will refer to these three concepts as:

- Shearless displacement
- Critical flame stretch (flame strength)
- Critical quench distance (flame standoff).

Each of these will now be briefly described.

• Shearless displacement--As a plane shock wave diffracts across a solid object, the pressure discontinuity is supported by fluid flow that, even very close to the surface of the object, is not appreciably affected by viscous shearing stresses; that is, the inertial forces dominate over the frictional forces, the former being many millionfold larger than the latter even for relatively weak shocks. If a flame is established over the solid object before the arrival of the shock, it can be swept cleanly away from its original location, leaving relatively cool air (and no fuel vapors) as the fluid medium adjacent to the surface of the solid object. If the dimension of the object along the path of shock propagation is small, the flames may be swept completely away from the burning surfaces, leaving them unable to continue combustion. However, if the burning surface is large, the flames may not be swept cleanly from the entire area that is capable of supporting flames. Hence the flames will quickly reestablish themselves following the brief interlude of shock diffraction and inertial flow.

Immediately behind the shock front, as it sweeps over an extended surface, a boundary layer forms in which friction with the surface slows

down the fluid near the surface relative to the free stream giving rise to a steep gradient in velocity and severe shear stresses. Eventually, but often in a time much shorter than the duration of the positive over-pressure phase, the velocity in the boundary layer slows to the point where the flame can remain anchored despite the shear stress. From that time and location, the flame begins spreading inexorably upstream to reestablish itself.

Critical flame stretch--In a theory of the extinction of diffusion flames by steady, laminar air flow (classical wind-tunnel conditions), Spalding⁸ postulates an upper limit to the combustion rate of any gaseous fuel in air, which he designates "flame strength." He shows that this limiting rate for diffusive burning is of the same order as the combustion rate of the same fuel in a stoichiometric premixed flame. The diffusion flame's location and its rate of combustion are determined by the physical transport processes (which are necessarily diffusive in the absence of turbulence) that control the rate at which the fuel and oxidant molecules encounter one another. Ordinarily, chemical reaction rates are comparatively so rapid that they may be considered to occur instantaneously on contact of the reactants, but in the velocity gradient of the fluid boundary adjacent to a solid surface, rates of physical mixing may become comparable to reaction rates. Then the flame seeks out a stable location closer to the solid surface (which is also the source of the gaseous fuel), and the resultant rate of combustion is higher. If the free-stream velocity is further increased, the flame moves still closer to the surface and the reaction rate increases until the critical rate of the chemical reaction is reached. At this point

⁸ D. B. Spalding, "A Theory of the Extinction of Diffusion Flames," Fuel 33, 255-273 (1954).

the flame will "break" and appear to be "blown downstream" to a new stable point where the velocity gradient permits the reaction to proceed at a rate less than the critical value. If then the free stream velocity is decreased (or if the condition of fluid-solid interaction causes the boundary layer to increase in thickness), the flame will reestablish itself, propagating against the fluid flow to more or less its original position.

The phenomenon of breaking of the flame sheet in a steep velocity gradient resembles the stretching of an elastic membrane to its limit of strength. This led Karlovitz⁹ to propose the term "flame stretch" and to quantify the break point in terms of the velocity gradient normal to the burning surface. This concept is entirely analogous to Spalding's, from which it is derived.

Perhaps the simplest illustration of this concept is a spherical solid in a uniform velocity stream of air. The point of highest shear stress is the upstream stagnation point. Here the flame will break when the free-stream velocity is sufficiently increased. The geometry is a convenient one because it lacks the ill-defined leading edge of a plate or any other flat-sided object.

Experiments have been conducted with spherical liquid drops and with spherical wicks of porous solids saturated with liquid fuels.¹⁰⁻¹²

⁹ B. Karlovitz, "Flame Stabilization in Fast Streams," Sixth Symposium on Combustion, p. 941 (Reinhold Publishing Corporation, New York, 1956).

¹⁰ D. B. Spalding, Fuel 32, 169 (1953).

¹¹ G. A. Agoston, H. Wise, and W. A. Rosser, "Dynamic Factors Affecting Combustion of Liquid Spheres," Sixth Symposium on Combustion, p. 709 (Reinhold Publishing Company, New York (1956)).

¹² H. C. Hottel, G. C. Williams, and H. C. Simpson, Fifth Symposium (International) on Combustion, pp. 101-129 (Reinhold Publishing Corporation, New York, 1955).

The critical free-stream velocity has been found to depend on sphere diameter and to vary with both the latent heat of volatilization of the fuel and the ambient temperature. In particular, the critical velocity, corresponding to a break in the flame at the forward stagnation point, has been found to increase with sphere diameter, to decrease on substitution of liquids fuels requiring more heat to vaporize, and to increase with ambient temperature.

Using kerosene as the fuel, Spalding¹⁰ found a direct proportionality between the critical velocity and sphere diameter. This he offered as evidence in support of his flame-strength theory of extinction. In contrast, Agoston, Wise, and Rosser,¹¹ using n-butyl alcohol as the fuel, observed extinction velocity to vary as the square root of drop diameter.

Aside from this unresolved contradiction, Spalding's theory satisfactorily accounts for the available experimental data on extinction.

Critical quench distance--Another plausible explanation for the experimental facts described above involves the quenching of flames within a small distance of a solid surface. The theory is not well advanced for diffusion flames, but there is a wealth of empirical information for premixed flames that can be explained theoretically, and it seems likely that some correspondence of principles will apply to diffusion flames.

Fundamentally, when an established flame burns in proximity to a solid surface that acts as a sink for heat and reactive intermediates, these may diffuse to the surface fast enough to lower the temperature and/or concentration of reaction intermediates below the level needed to maintain a stable flame, and extinction occurs. At atmospheric pressure, these distances are the order of millimeters. In Spalding's experiments¹⁰ with kerosene-wetted spheres, the distance separating the liquid surface from the visible flame had a minimum value of about

0.036 inch (~ 0.9 mm) immediately before extinction, regardless of the drop diameter. Agoston et al.¹¹ report the same constant separation distance for porous spheres wetted with both ethyl alcohol and n-butyl alcohol. Reporting on experiments on burning of cellulosic solids, Parker¹³ estimated the standoff distance for visible flames at about 1 mm.

¹³ W. J. Parker, "Flame Spread Model for Cellulosic Materials," Spring Meeting of the Central States Section/The Combustion Institute, University of Minnesota (March 1969).

EXPERIMENTAL APPROACH

We plan to complete and use the SRI blast/fire shocktube to investigate extinction phenomena and conditions suggested by current theories. Several idealized simulations of fires and fire/fuel geometries will be used to establish the appropriateness of the proposed extinction concepts and, as appropriate, to develop empirical scaling rules.

For example, we propose to use spherical wicks of varying diameter saturated with liquid and/or gaseous fuels representing a range of values of Spalding's mass-transfer B number and "flame strengths." The resulting data will be compared with the extinction responses of solid spheres of PMMA, Delrin, and cellulose. These model polymers are chosen because they represent an interesting range in the properties of urban fuels and because their effective latent heats of vaporization, the so-called "heats of volatilization" are well established experimentally.

Other configurations to be used may include flat fuel beds arranged longitudinally to the path of the shock. These may be both solid fuels and liquid fuels and could include liquid fuels on solid wicks.

The Attachment (Summary Final Report, Shocktube for Blast-Fire Interaction Studies, August 30, 1974) describes the shocktube's capability to independently vary overpressure, positive-phase duration, and particle velocity. A schedule of variation of these parameters will be used to explore the empirical dependencies.

APPENDIX C

THERMAL SIMULATION FACILITIES*

The following material summarize the current status of the facilities available to simulate the thermal radiation emitted from a nuclear weapon burst.

- Tri-Service Thermal Nuclear Flash Test Facility
- Explosive Light Source (ELS)
- Miscellaneous Facilities for the Simulation of Nuclear Burst Thermal Radiation.

* This material was kindly supplied by Don Sachs of Kaman Nuclear

TRI-SERVICE THERMAL NUCLEAR FLASH
TEST FACILITY

[Reference: DNA-4488Z, Interim Summary Report, 29 March 1978]

- University of Dayton built and operates the facility located at Air Force Materials Laboratory, Wright-Patterson AFB, Ohio. The work was funded by DNA/SPAS (Maj. D. Garrison and Capt. J. M. Rafferty were contract monitors).
- Objectives:
 1. To provide the Tri-Service community with a quick-response, intense radiation heating experimental capability, including the effects of aerodynamic and mechanical loads;
 2. To conduct tests for the Tri-Service community as required; and
 3. To generate a data base of the response of typical materials exposed to nuclear flash environments.
- As of early CY78, the Facility has four basic experimental units operating:
 - (1) Irradiation of test specimens using a Quartz Lamp Band (QLB);
 - (2) Irradiation of test specimens using a QLB in aerodynamic flow;
 - (3) Irradiation of test specimens using a QLB with tension or bending mechanical loads; and

(4) Irradiation of test specimens using an Arc Imaging Furnace (AIF).

● Quartz Lamp Banks

Two banks are now available - one is stationary and the other mobile. The banks produce a one-dimensional radiation source area of about 15 cm by 12 cm; the incident radiation heat flux on a test specimen can be as high as $35 \text{ cal/cm}^2\text{sec}$.

● Arc Image Furnaces

Two arc image furnaces are available; both utilize carbon arcs as radiation sources, thereby producing a different wavelength spectrum than produced by the tungsten filament quartz lamps. The Gaussian Beam Arc Imaging Furnace (GBAIF) is capable of producing a radiant heat flux up to about $140 \text{ cal/cm}^2\text{sec}$. Typical specimen sizes are 2.5 cm by 2.5 cm square. Exposure times may vary from 0.1 secs to about 20 secs; the time is accurately controlled by a water-cooled shutter, producing a square wave profile in time.

The One-Dimensional Beam Arc Imaging Furnace (ODBAIF) uses one mirror to produce an essentially parallel-light radiation test device. The beam diameter is about 30 cm with a constant heat flux of about $1 \text{ cal/cm}^2\text{sec}$. A shutter is used to produce a square wave profile, similar to GBAIF.

- Aerodynamic Load Simulation

An open-circuit, pull-down wind tunnel is available to simulate aerodynamic flow over specimens exposed to high intensity radiation. The 30-cm long test section has a 2.38-cm by 11.43-cm cross section. The constant freestream velocity is nominally 240 m/sec (M 0.7). The Reynolds number can be varied from 2×10^6 to 18×10^6 .

The mobile QLB is used in conjunction with the wind tunnel; specimen sizes up to 11.4 cm by 10. cm can be accommodated. Heat flux levels up to $40 \text{ cal/cm}^2\text{sec}$ are readily achieved.

- Mechanical Load Simulation

A creep frame is available for dead weight simulation of tensile and bending loads on specimens. The mobile QLB is used as the radiation source. Uniaxial tension stress levels are 3.5 to 1700 MPa and bending (tension or compression) stress levels are 7 to 1400 MPa.

- Projected Facility Improvements

During FY78 and FY79 several facility improvements are projected:

- (a) Increased Heating - Increased heat flux levels of quartz lamp banks.
- (b) Shutter - A water-cooled shutter will be added to QLB to allow for better pulse shaping.
- (c) Surface Phenomena Photography - Motion picture photography capability will be added.

- (d) Strain Measurement - Temperature-compensated strain gages and/or use of LVDT-type deflectometers will be considered.
- (e) Surface Temperature Pyrometry - A recording optical pyrometer system, to measure high surface temperatures of test specimens, will be installed.
- (f) Solar Furnace - The solar furnace is available, but must be wired up and checked out. The furnace uses a carbon arc for the radiation source, which closely simulates the nuclear flash blackbody temperatures.
- (g) Simultaneous Aerodynamic and Mechanical Loading - The ability to simultaneously expose specimens to radiant heating, aerodynamic shear and mechanical loads is desirable and will be implemented.

EXPLOSIVE LIGHT SOURCE (ELS)

[Reference: Presentations at the 1977 Satellite Diagnostics Working Group Meeting held at the Air Force Technical Applications Center, Patrick AFB, Florida on 5 April 1978, by Mr. John Dishon, Science Applications, Inc., and Mr. Ronald F. Glaser, Sandia Corporation-Albuquerque]

- Objectives:

1. To provide an intense, short-duration thermal radiation source which is capable of irradiating large military specimens and/or structures;
 2. To design the construction of the source elements so that the source is mobile or can be easily set up at remote test locations;
 3. To conduct field tests of the source, varying the source dimension, bag geometry, and chemical parameters, and measuring the source output vs. time and space.
- The reference presentation provided information on the early designs of the ELS, a description of four specific events conducted during the period 28 February to 6 March 1978, and the data from those events collected by Sandia. The information presented here is taken from the reference presentation.

- ELS Background

- Peak Power: 6×10^6 to 1×10^9 watts
- Spectrum: Blackbody of 3800° to 4000°K
- Mechanism: $2 \text{ Al} + 3/2 \text{ O}_2 \rightarrow \text{Al}_2\text{O}_3 + \text{Light (34\%)}$
- Two-Pulsed Unit
- Size: 2-ft Sphere to 200-ft Linear Array

- ELS Characteristics

PULSE	POWER RANGE (WATTS)	RISE TIME (MSEC)	FLUX RATE (W/SEC)	DECAY TIME (MSEC)
Primary	$6 \times 10^6 - 1 \times 10^9$	2.0-4.0	$3 \times 10^9 - 5 \times 10^{11}$	30
Secondary	$2.5 \times 10^7 - 1 \times 10^9$	25-400	$5.25 \times 10^7 - 4 \times 10^{10}$	3000

- Results of the February-March 1978 ELS Tests

The ELS primary pulse array for these tests measured 40 ft wide by 12 ft high and the secondary pulse array was about 44 ft wide by 20 ft high. These arrays were positioned parallel to each other, separated by 50 ft.

The results of these events are listed in the Table below; in all cases the data presented are averages of the detailed measurements obtained by Sandia.

EVENT	1st PULSE PEAK POWER (WATTS)	2nd PULSE PEAK POWER (WATTS)	(\sqrt{Y} peak) FLUX RATE (WATTS/SEC)	1st MAX (MS)	MIN (MS)	2nd MAX (MS)	DETECTORS TRIGGERED
1	1.6×10^8	2.1×10^8	6.6×10^{10}	2.4	98	359	5
2	8.7×10^7	1.2×10^7	2.9×10^{10}	3.0	41	187	3
3	1.2×10^8	4.1×10^7	4.1×10^{10}	2.9	24	74	4
4	1.5×10^8	1.5×10^8	5.1×10^{10}	2.9	37	343	7

The Sandia amplitude vs. time measurements were obtained with the following instrumentation:

- (a) Super Suitcase, Optical (2 each)
- (b) Old-Style Suitcase (former YSRM) (3 each)
- (c) Nuclear Burst Detection System (NBDS) (3 each)

• Conclusions from the February-March 1978 ELS Tests (as stated by SLA)

1. Regarding the first pulse rate of rise, the ELS (as detonated at SLA) has a slow rise compared to Bhangmeter requirements to detect nuclear bursts.
2. Regarding the second pulse shape, the 8-bag ELS detonated at SLA showed considerable shape variability; the 40-bag ELS should show improvement.
3. Regarding the optical/yield scaling, it appears that the ELS optical source strength increases as approximately $(Y)^{2/3}$. Looking at relative source strengths, one can list:

<u>EVENT</u>	<u>SOURCE</u>	<u>SOURCE STRENGTH</u> (WATTS-SILICON)
ELS	1-bag (6-shots-Ave.)	7×10^7
ELS ($Y^{2/3}$ scaling)	8-bag (scaled from 1-bag)	2.8×10^8
ELS	8-bag (measured)	2.1×10^8
ELS ($Y^{2/3}$ scaling)	40-bag (scaled from 1-bag)	8.2×10^8
Nuclear Burst	2nd Max. (1 KT)	1.8×10^{13}
DICE THROW	630-Tons ANFO	1.2×10^{10}
PRE-DICE THROW II	120-Tons ANFO	7.1×10^9
Lightning	Return Strokes	$1 \times 10^8 - 1 \times 10^{12}$

● Near-Term Projected Testing

- (a) SAI and SLA performed some ELS test events at Fort Ord (California) during April-May 1978. The main test elements included: (1) Alternative designs of the ELS array; (2) Larger source arrays; (3) Measurements of direct/scattered radiation ratios; (4) Measurements of range dependence and radiation symmetry; (5) Measurements of optical/yield outputs to determine scaling relations.
- (b) SAI will participate, with ELS arrays, in the Misers Bluff event planned for late June 1978.

MISCELLANEOUS FACILITIES FOR THE SIMULATION OF NUCLEAR BURST THERMAL RADIATION

In addition to the two primary simulation facilities mentioned in the preceding paragraphs, there are a few other possible facilities around the U. S. which could be used to simulate thermal radiation from a nuclear burst.

- Lasers (of various varieties)

The CO₂ laser has been used in the past for materials testing, where high fluxes are imposed on very small specimens. An unfocussed beam would approach 1-cm diameter and could emit about 100 watts/cm², continuous or pulsed. The radiation would be monochromatic in the 10μ wavelength region, which means that the radiation coupling efficiency would be high for organic materials.

- Solar Source

Sandia Laboratory (Albuquerque) has erected an array of flat mirrors, covering an area about 13 ft square. This facility is designed to produce a relatively low flux (less than 5 cal/cm²sec) over this large area.

- Carbon Arc Furnaces

- (1) The carbon arc furnace, formerly located at NASL, was moved to NSWC (White Oak) when NASL closed. This furnace has not been used for the last 3 to 4 years, but laboratory personnel state that it could be made operational, if required.

- (2) The carbon arc furnace, formerly located at NRDL, was purchased by Stanford Research Institute when NRDL closed. This furnace has since been declared surplus and is not usable.

Appendix D

OBJECTIVES FOR PREPAREDNESS AND THEIR IMPLICATIONS
FOR CIVIL DEFENSE DESIGN OPTIONS

A paper originally presented
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By

Clifford E. McLain
Deputy Director
Defense Civil Preparedness Agency

As you are all aware, much recent study has been devoted to the questions of civil defense and, indeed, such studies are still continuing. A recently completed study by the Department of Defense examined a number of design options which would provide for the survival of a major fraction of the total U. S. population in the event of a general nuclear exchange between the U. S. and the Soviet Union. In addition, there are current studies as to the strategic roles which might be played by civil defense and as to appropriate organizational designs for civil defense/emergency preparedness management. Decisions as to the role, objectives, and organization of civil defense are expected in the very near future.

Assuming that specific decisions are made establishing both the objectives and basic functional requirements to be met by a civil defense/emergency preparedness system, and a schedule for the installation of such a system, we will then have the task of developing and deploying something which actually works. The notice that one's head will be put on the block of actual performance assessment is always a sobering experience for any design engineer. Safety margins and design conservatism become matters of significant impact once the operational date and specific performance requirements have been established. At the Federal level, at least, civil defense has not been subjected to specific performance testing of a complete system, even though test exercises and interaction on a "dual use" basis with peacetime emergencies have been effective in limited testing of some civil defense functional elements.

FUNCTIONAL CHARACTERISTICS OF A WORKING CIVIL DEFENSE SYSTEM

If the system is actually intended to work, let's first examine what its general functional characteristics should be. The functional characteristics of a civil defense system (as opposed to functional elements such as communications, shelters, stockpiles, emergency services, etc.) may be defined as those end functions of the system which determine its overall worth and effectiveness. They may be listed in the following fourfold manner:

- o Reduce the targeting efficiency of the threat, to protect the population
- o Good false-alarm tolerance
- o Continuity of emergency services
- o Enhanced recovery capability

If the civil defense system is to function in any strategic sense at all, it is almost a truism to say that it must distribute people, industrial facilities, whatever elements of the national civil structure are to be preserved, so as to reduce the efficiency with which these elements can be targeted. Only in the case of very hard systems (Minuteman Silos, for example) can a

resource remain as a target and maintain a finite probability of survival through attacking system limitations (accuracy, yield, numbers assigned per target, etc.). Furthermore, the manner in which it reduces the targeting risk of such elements must be such that the effectiveness of the system cannot be negated by retargeting. This latter point is important if pressures on the adversary to increase the weapons inventory needed to hold the protected elements hostage are to be avoided (i.e., if very large increases are necessary, the adversary may give up attempts to retain targeting risk for these protected elements).

A second important functional characteristic, really applicable to any emergency system, is that it have a good false-alarm tolerance. The system must be capable of being turned on (to an alert or protected status) without disastrously affecting the national or local welfare through this act alone. Can the civil defense program be activated to place national civil resources under greater protection in times of maximum tension or actual attack intelligence without imposing unacceptable effects from the activation itself? If it cannot, the system will likely never be turned on.

Continuity and effectiveness of emergency services must be preserved by any functional civil defense system. Requirements for such services will be intense during both the activation period for the civil defense system (i.e., from initial warning to actual attack or "all clear" intelligence) as well as the obvious requirements for attack survival and recovery. The operation of the system to remove national elements (as population) from targeting must at the same time preserve the coherent responsive capabilities of the essential emergency services, such as medical care, firefighting, law enforcement, rescue operations, and the like.

Finally, the ability of the system to prepare is essentially the ability of the system to enhance survival. It is further suggested that survival can, in the ultimate sense, only be defined in terms of recovery capability. The overall preparedness capabilities of the system can only be achieved through designs which consider and meet the functional requirements of recovery which includes the extension to long-term survival.

A BRIEF HISTORY OF THE DEVELOPMENT OF THE U.S. SYSTEM¹

If the foregoing may be said to have established general functional characteristics of an operational civil defense system, how have these functional characteristics appeared in the actual development of the U. S. civil defense program?

The earliest formal Federal action for civil defense was taken August 29, 1916 when Congress created the Council of National Defense (39 Stat. 649; 50 USC Ch. 1), composed of Secretaries of War, Navy, Interior, Agriculture, Commerce, and Labor. The Council was charged with coordinating industries and resources for the national security. Following the declaration of war, April 6, 1917,

¹ This historical detail is more completely outlined in "Significant Events in U. S. Civil Defense History" published by the Defense Civil Preparedness Agency, July 1, 1975.

the Council requested all State Governors to establish State councils. State and local units were organized in all States, but these rapidly dissolved following the Armistice of November 11, 1918. However, the Council of National Defense continued in operation well into the WWII period.

The next formal actions took place just prior to the entry of the U. S. into WWII with the establishment of the Office of Emergency Management within the Executive Office, by Executive Order 8248, September 8, 1939. The office actually became active in May 1940. An advisory commission was appointed to the Council of National Defense and State organizations were established throughout 1940. In June 1941, the Lanham Act was passed providing \$150,000,000 for community facilities for civil defense activities. An Office of Civilian Defense (OCD) was established (EO 8757) within the Office of Emergency Management, with Mayor LaGuardia of New York named as Director.

During WWII, civil defense operations were rapidly expanded with organizational extension to the community level through volunteer "block wardens," aircraft spotters, and like functions. Shortly following the victory in Europe (V-E Day), May 8, 1945, the OCD was abolished and State and local organizations subsequently disbanded. Following WWII the U. S. perceived the need to maintain civil defense activities, particularly in the event of possible atomic weapon warfare. The Office of Civil Defense Planning (OCDP) was created on March 28, 1948 to plan for national security. One year later (March 3, 1949) civil defense planning was assigned to the National Security Resources Board (NSRB).

Finally, on September 8, 1950, PL 774, Defense Production Act of 1950 proposed a national civil defense plan. PL 875, September 30, 1950 authorized Federal assistance to States and local governments in major disasters. Executive Order 10185 (Dec. 1, 1950) created the Federal Civil Defense Administration (FCDA) within the Office for Emergency Management, in the Executive Office of the President. On December 16, 1950 (EO 10193), the Office of Defense Mobilization was also established.

On January 12, 1951, President Truman signed the Civil Defense Act of 1950 (PL 920, 81st Cong.) establishing FCDA as an independent agency in the Executive Branch of the Government. During 1951, FCDA set about creating an effective working organization at national, State, and local levels. Training programs were started, and a partnership basis of support was initiated. FCDA established a regional organization with 9 regional directors. Executive Order 10427 of Jan. 16, 1953, gave FCDA responsibility for providing assistance to localities stricken by major disasters under PL 875; and Executive Order 10737, of October 29, 1957, expanded functions of FCDA in administering disaster relief under PL 875. On July 1, 1958, EO 10773 placed all civil defense functions in the Office of Civil and Defense Mobilization (OCDM), established by PL 85-763 (August 26, 1958). At the same time (August 8, 1958), PL 85-606 vested civil defense responsibility jointly between States and the Federal Government, and authorized financial contributions to States for necessary personnel and administrative expenses (P&A funds) and for reimbursement of expenses of students attending civil defense schools (Student Expense Program).

Organizational modifications continued with the assignment of responsibility for civil defense to the Secretary of Defense, under an Assistant Secretary

of Defense, and the reconstitution of OCDM as a small Executive Office staff coordinating function as the Office of Emergency Planning (OEP), under EO 10952, effective August 1, 1961 (the OEP was later approved by PL 87-296, September 22, 1961). A vigorous program for the survey and establishment of fallout shelters was begun as a result of the Berlin Crisis. This was added to in late 1962 in response to the Cuban Missile Crisis. Major funding increases were provided for shelter identification and for emergency food and medical stockpiles. This vigorous effort was largely completed by the end of 1963. On April 1, 1964, the Secretary of Defense transferred all civil defense responsibilities (assigned to him under EO 10952) to the Secretary of the Army, who subsequently established an Office of Civil Defense. The OEP continued to exist in the Executive Office of the President.

Executive Order 11490, October 28, 1969 assigned emergency preparedness functions to a variety of Federal departments and agencies and superseded all previous EO's on the subject. On May 5, 1972 the Secretary of Defense established the Defense Civil Preparedness Agency (DCPA) as an independent DOD agency responsible for civil defense reporting to the Secretary of Defense and the OCD in the Army was abolished. Further distribution of functions was accomplished in 1973 under EO 11725 (June 27, 1973) which transferred the functions of the OEP to HUD, Treasury, and GSA. Authorized were: Federal Disaster Assistance Administration (FDAA) under HUD, to administer national disaster relief functions, and the Office of Preparedness (OP changed to the Federal Preparedness Agency, FPA, July 1, 1975) under GSA.

In all of the foregoing history of actions, the Federal involvement in civil defense was viewed primarily as providing for an effective system to mitigate loss and facilitate recovery in the event of nuclear attack. Yet, State and local governments had been encouraged to combine defense and peacetime preparedness functions in a single organizational structure (i.e., not to maintain a separate structure for nuclear attack problems only). The close practical parallelism between nuclear attack and peacetime emergency functional requirements were recognized early in the history of the program. In more recent history, formal recognition of the "dual use" of the U. S. civil defense system was established by a 1976 amendment to the Civil Defense Act of 1950 (Sec. 804(a), PL 94-361, 90 Stat. 931), approved July 14, 1976. This amendment specifically recognized the "dual use" aspect of civil defense as a partnership approach by Federal and State governments "... to provide relief and assistance to people in areas of the U. S. struck by disasters other than disasters caused by enemy attack."

What are the conclusions to be drawn from this brief historical outline?

1. The general desirability of maintaining some form of civil defense operations and planning has been continuously recognized.
2. Major buildups in support have been directly derived from immediate perceived threats (the Berlin Crisis, the Cuban Missile Crisis).
3. The program has principally addressed the question of population survival. Continuity of government has received some study. Very little

has been done on industrial/economic survival.

4. At no time were any specific performance goals established for civil defense (i.e., against threat T, X% of the population survives with probability P).

CURRENT PROGRAM STATUS

The current situation of civil defense in the U. S. is that a system exists which partially provides a basis for effective expedient "surge mode" actions if sufficient time and resolve were provided between strategic warning and attack. In a one-to-two week period of action and national resolve from warning to attack, the current program provides for: saving about ten million lives, a minimal probability of survival for the Federal Government teams deployed in the protective arc around the National Capitol, a reasonable probability of survival for the President, and essentially no protection of industry or the economic base. Certain of the currently existent crisis relocation plans are probably subject to retargeting. The current relocation facilities for preserving the continuity of the Federal Government are very vulnerable to a deliberate Soviet attack against the Federal Government. No highly survivable C³ and resource inventory and allocation system currently exists by which recovery could be managed from a national center immediately following an attack.

In part, this current U. S. civil defense position may be said to be a logical development from the so-called "mutual assured destruction posture." "Massive retaliation" was, in a sense, an initial phase of the same policy when U. S. strategic forces were preponderant immediately following WWII. This posture emphasizes peacekeeping through force of strategic offensive armaments and argues that general nuclear war must be made "unthinkable." Thus, in general, the populations and industrial/economic resources of the strategic adversaries would be the targets upon which deterrence would be based. Any significant action to effectively remove population or industrial/economic base from retaliatory targeting would thus be regarded as destabilizing.

Recent assessments of Soviet civil defense actions and their general strategic philosophy have led to a reexamination of the U. S. position. Regardless of the actual performance potential of Soviet strategic systems, and civil defense, a Soviet view of deterrence based on "war fighting" capability, rather than mutual assured destruction, would clearly introduce an asymmetry of perceptions in the strategic balance between the U. S. and the Soviet Union. Some have argued that such a real difference exists. ("A Dangerous Delusion"--Adm. Elmo R. Zumwalt, USN(Ret), Saturday Evening Post, November 1977; "Civil Defense in the Soviet Union" -- C.N. Donnelly, International Defense Review Vol. 10, No. 4, Aug. 1977; "Soviet Civil Defense: The Grim Realities"--John G. Hubbell, Reader's Digest, Feb. 1978.) It has also been argued by some, that if options other than mutual assured destruction are to be made available to the President, (i.e., significant reductions in nuclear arms, more limited attack/response scenarios, etc.) such options

should not place the general U. S. population and industrial base at risk and, therefore, require an effective civil defense system. For these and other reasons, some have argued that civil defense should form an integral active part of the structure and operational capability of U. S. strategic forces. ("Legislation Introduced to Provide for a Comprehensive 7-Year Civil Defense Program"--Congressman Donald J. Mitchell, 31st District-N.Y.--Congressional Record H1672-1676 March 3, 1978; "Nuclear War, The Life and Death Issues"--Edgar Vesamer, Air Force Magazine, Jan. 1976).

In any event, regardless of whether the rationale is based upon perceptions that civil defense is a necessary part of the U. S. strategic posture or upon a desire to have an effective "insurance policy", a decision to deploy an effective civil defense capability clearly requires a new and more vigorously supported civil defense program. The current program lacks the capability of performing such functions effectively. For all options, it is apparent that effective civil defense operations will require strong national resolve and the acceptance by State and local governments that a rational requirement for nuclear attack preparedness exists. At a minimum, improved provisions for Federal strategic stockpile management and continuity of Federal Government appear to be absolutely necessary, even under current civil defense policy

PRINCIPLES OF SYSTEM DESIGN

Assuming a decision to deploy a civil defense system designed to meet performance criteria (and recalling that such an objective has never been formally assigned in the past), we must establish a set of functional requirements which can be used to describe the system before its detailed design can be rationally undertaken. It was noted in the preceding section that these functional requirements might be defined as:

- . Reduce the targeting efficiency of the threat
- . Good false-alarm tolerance
- . Continuity of emergency services
- . Enhanced recovery capability

All of these basic functional characteristics can be defined in terms of a specific performance requirement. The question of specific design tradeoffs can only be dealt with rationally if some set of such performance requirements are not stated by at least defining the boundaries within which predicted performance should lie. A mix of quantitative and qualitative descriptions may be necessary. For example:

Protection: X % of population survives threat T with probability P

False Alarm: Relocation on warning has a one-time cost of $\$M$ and a carrying cost of $\$Y$ for a maximum of t weeks - Recovery time t to normal following alert.

Emergency Services: Specification of minimum health, police, fire-fighting performance to be preserved as a function of host area plan.

Enhanced Recovery: Recovery time of K weeks against threat T.

From the basic functional characteristics previously described, some derivative principles of design may be established for general civil preparedness systems which are intended to meet the threat of nuclear attack. In summary, these principles may be generally stated to be:

- . Distributed targets (enforced low unit warhead efficiency for the attacker).

- . Distributed adaptive functions (those functional units and elements which remain can reform themselves quickly into an operating civil system).

- . Autonomous operational capability for individual units, areas immediately following attack.

- . Minimization of required communication bandwidth through delegation of information processing, decision functions, resource allocation to lowest possible level.

- . Local damage assessment, resource allocation.

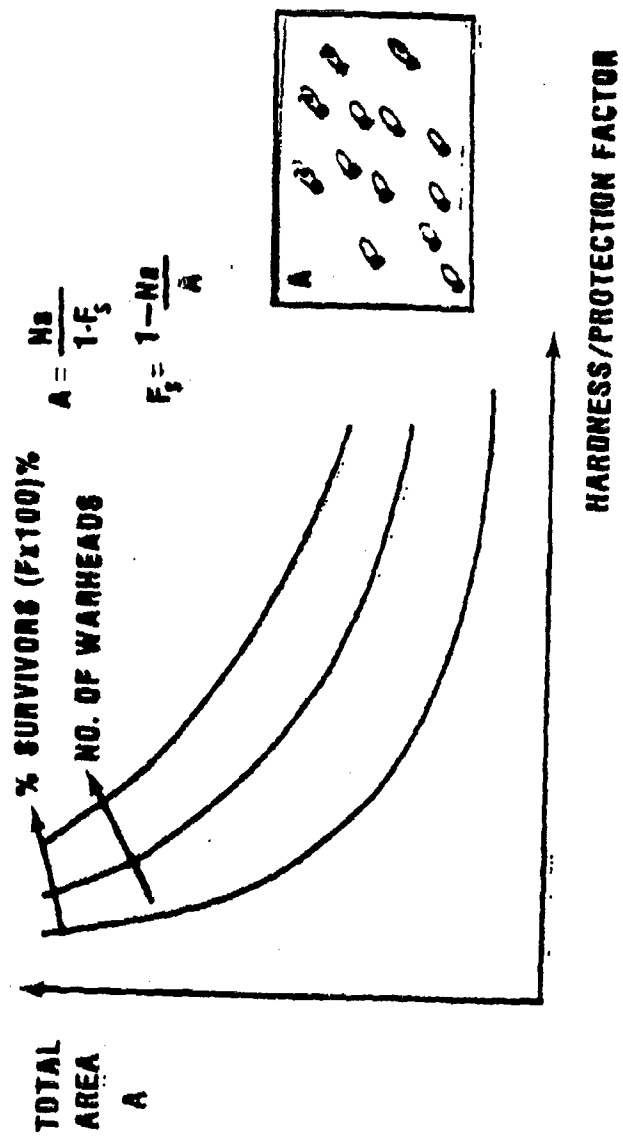
- . Redundant critical information storage.

All of these principles are, of course, corollaries of the basic theorem that lowering the density of the target distribution is the mechanism by which targeting risk by any given threat level is reduced.

What are the implications of these principles for specific civil defense system designs? First, the methodology for distribution can be most simply examined in terms of a uniform distribution of population or other resource over an area which is large with respect to that which can be brought under targeting risk by the threatening strategic forces. This is essentially the design basis applied to deceptive basing of strategic systems (SSBNs on patrol, bombers in flight, the MX tunnel based system). The effectiveness of such a distribution is described by the simple notion (see fig. 1) that over a total area A, population P is uniformly distributed (or targets occur with uniform probability) with a uniform "hardness" such that $(\frac{P}{A})a$ is at risk for a single warhead, where a is the area subject to nuclear blast and fallout effects which exceed the uniform hardness of the distributed targets or population. Thus, for an attack of N nuclear weapons of uniform yield arriving at area A, the fraction of the uniformly distributed population or other targets which will be destroyed will not exceed $\frac{Na}{A}$ (this assumes a "cookie cutter" kill probability distribution such that all population or targets within area a are destroyed and all outside survive--other "real" survival probability distributions yield essentially similar results when $A \gg Na$). Of course, the surviving fraction of the distributed population $F_s = (1 - \frac{Na}{A})$.

FIGURE 1

UNIFORM DISTRIBUTION TOTAL AREA TO PROTECT FRACTION F_s OF POPULATION



The trade-off between the "hardness" of the distributed population (which determines the unit risk area, a) and the total area A , required to preserve a desired fraction of surviving population or other targets against an arriving attack of N warheads, is qualitatively illustrated by Fig. 1. In fact, classical CRP--out of the cities and into rural "host areas"--would be unnecessary if shelters of sufficient hardness (both blast and fallout) were uniformly distributed throughout the urbanized risk areas. Using 1975 population figures, total population in urbanized areas (pop. over 50,000) was about 124 million--within a total area of 35,000 square miles. If three-fourths of the total urban population were to survive, again using the very simple assumption of 100 percent survival outside of the unit weapon risk area a , the total permissible risk area, N_a , would be about 9,000 square miles, which could be achieved against 2,000 1 MT weapons with a uniform hardness level of about 30 psi and corresponding fallout capability. Such a system would be expensive--on the order of a few hundred dollars per person--but it would permit sheltering within the general urban area.

However, an actual uniform "soup" of population or other targets cannot be spread over the entire distribution area. In a practical sense, population will have to be grouped in finite clumps within protective facilities. Can these clumps be effectively targeted so as to place a higher percentage of the redistributed (crisis relocated) population at risk? Assuming that no two clumps occur within a single unit weapon risk area a , and that each clump can be fully destroyed by a single weapon (i.e., lies fully within a), the fraction of clumped population at risk is obviously the ratio of the number of arriving weapons to the number of clumps, M , assuming clumps of uniform size. The surviving fraction $F_s = 1 - \frac{N}{M}$.

Therefore, for distributed systems, the effective threat to clumping ratio $\frac{N}{M}$ must be low enough that the desired fraction of population is saved. This is, of course, exactly the same principle as that of the design of a multiple launch point deceptive based ICBM system. For this reason, if existing host facilities are to be used, the CRP plan must be carefully examined to make sure that the actual population redistribution achieved is insensitive to retargeting.

It should also be noted that if extremely hard protection facilities are used, one can depart from the dispersion design philosophy and instead base survivability on a low-kill probability of the strategic weapon used against the target, i.e., the accuracy and yield of the weapon will not produce a high fatality rate against the hardened shelter. This is the survivability principle of the current hardened land-based strategic missile forces. Such an approach has two problems as a civil defense solution (1) it is extremely expensive, and (2) it is hostage to qualitative improvements in the threat: warhead accuracy and yield.

Assuming that a civil defense system has been acquired which meets these basic survival requirements just discussed, what are the preparedness

requirements to insure its efficient utilization? The critical functional elements certainly include:

- . Warning -- time commensurate with distributed system design requirements.
- . Decision structure -- for control.
- . Dispersion plan -- to achieve removal from targeting.
- . Shelters -- to achieve the required hardness for the dispersion plan.
- . Stocking -- to permit shelter survival through post attack radiation hazards.
- . Environmental sensing -- to permit optimum safe recovery operations.
- . Training and incentives for CRP -- to insure compliance with the population distribution plan.
- . Shelter management techniques -- to insure conditions which will encourage adherence to safety and good survival practice.
- . Emergency Services -- medical, firefighting, etc.
- . Record and information retrieved -- for recovery.

The required hardness for the survival of distributed population or other potentially targeted resources may be achieved either through previously installed shelters or facilities (undoubtedly required for higher hardness levels) or expedient protective facilities, prepared as a part of the relocation action itself. The time to prepare these expedient facilities must, of course, be included in the overall reaction time of the system (i.e., the time to achieve the designed protection level from the decision to activate the system).

If the bombs actually fall, these systems and preparations should succeed in preserving the design fraction of population and other resources protected against the nuclear exchange risk itself. But of what use are the surviving population and facilities if a viable political and economic fabric cannot be restored? It is clear that, initially, most of the direct connective networks serving the Nation; electric power, gas and oil pipelines, long line communications, surface transport of goods (major rail and highway routes), etc. will be severed. Furthermore, economic recovery will require quick reference to and evidence of financial resources, property holdings, and all of the fabric of the modern economic world. Therefore, if survival

is to have meaning in the sense of recovery, the preparedness system must establish the facilities required for rapid recovery in such a way that they too, survive and maintain their utility after the attack. If this is to be achieved, the recovery resources must follow the same design principles as those required for basic population or resource survival. They must be distributed so that adequate survival will be assured regardless of the way in which the threat is targeted, and the elements which survive must be adaptive in character; that is, an entire working system must be formable from the fraction of resources remaining. Therefore, a distributed, adaptive system is required.

Figure 2 is illustrative of the problem. It shows a representative segment of the current DCPA/civil defense land lines communications system. In peacetime and for warning it is an efficient system. Note, however, that its nodes and major lines lie in or pass through high risk target areas. In the event of an actual general attack, few, if any, of these channels would remain. However, if a fabric or network of alternate channels is overlaid, having numbers of lines and nodes large with respect to the total threat and having a characteristic size of its fine structure which is significantly smaller than the mean distance between high threat areas, this network will survive. Even though it has large holes blown in it, continuous communications will still be possible--although, perhaps through less efficient routes than with the current trunk and branch linear system. Facilities for the construction of such a system in many cases already exist, in the emergency radio and ham radio activities, for example.

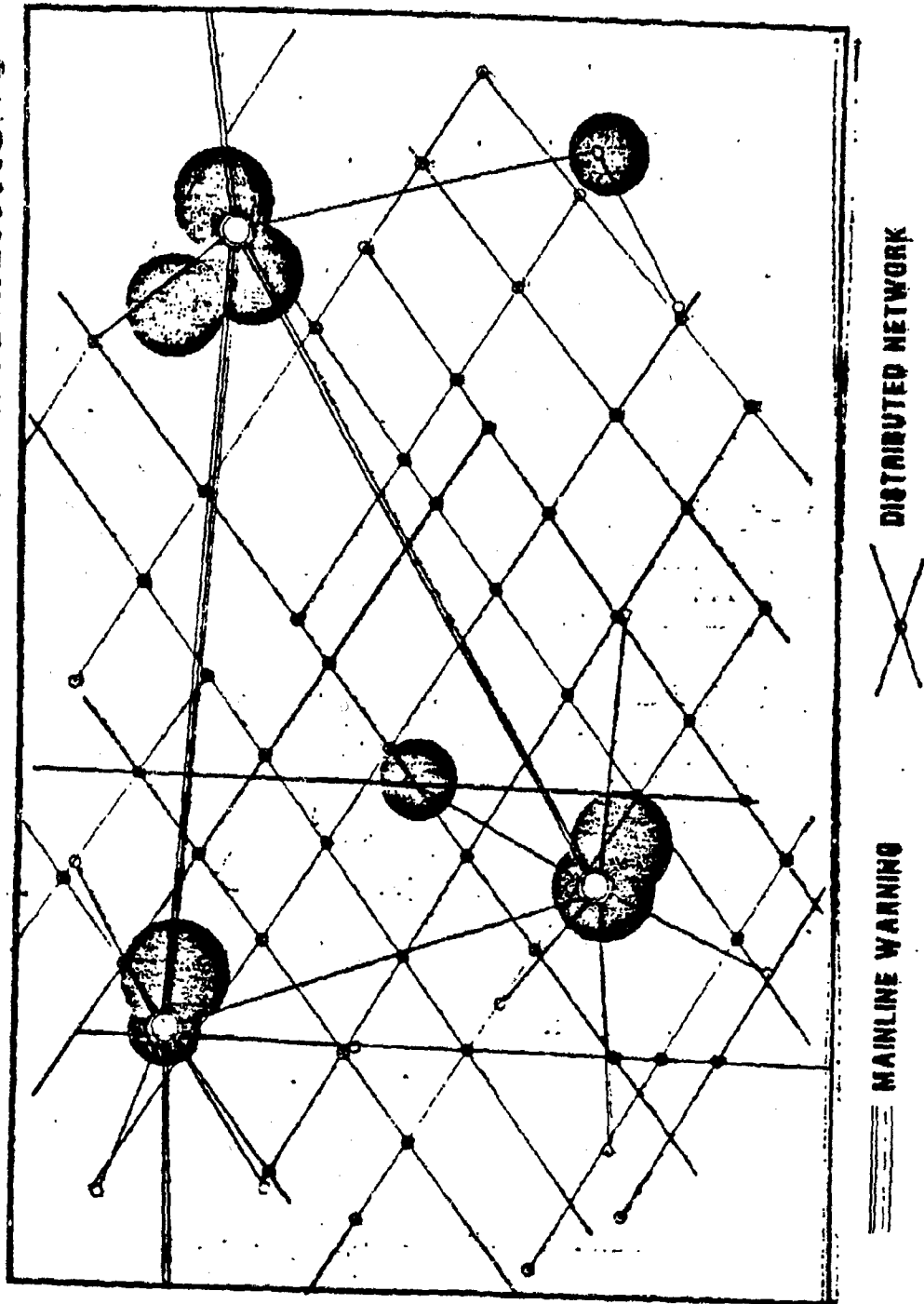
Similarly, some means should be developed for massive redundancy and security for vital records and economic and financial data. Currently, many large financial institutions provide for duplicate record maintenance in at least one alternate secure site. But, how well can the interrupted threat of current economic and financial activity be picked up from these repositories? And, can a single duplicate unit provide adequate survival probability? It is possible that, if all financial institutions (banks, etc.) will provide an alternate record repository with balanced hardness dispersed randomly in the "non-risk" areas, the large numbers of these in comparison with the threat warheads will insure survival of a major fraction and that this major fraction will be a sufficient basis upon which to restore the economic and financial system. Further redundancy would, however, seem to be a wise move.

DESIGN CONSIDERATIONS OF COST AND PERFORMANCE

How may such civil defense systems be expected to perform as a function of cost? A number of sample designs have been roughly priced and evaluated against a nominal massive attack against military targets and urban/industrial centers. The results of these assessments in terms of percent of total population surviving is shown in Figure 3. For purposes of this discussion, only the relative results (not absolute values) are important. Very inexpensive systems (Systems A and B) do not save much of the population. Fallout protection alone is not enough to provide a significant improvement for an in-place system over no system at all. System C, relocation to farms and

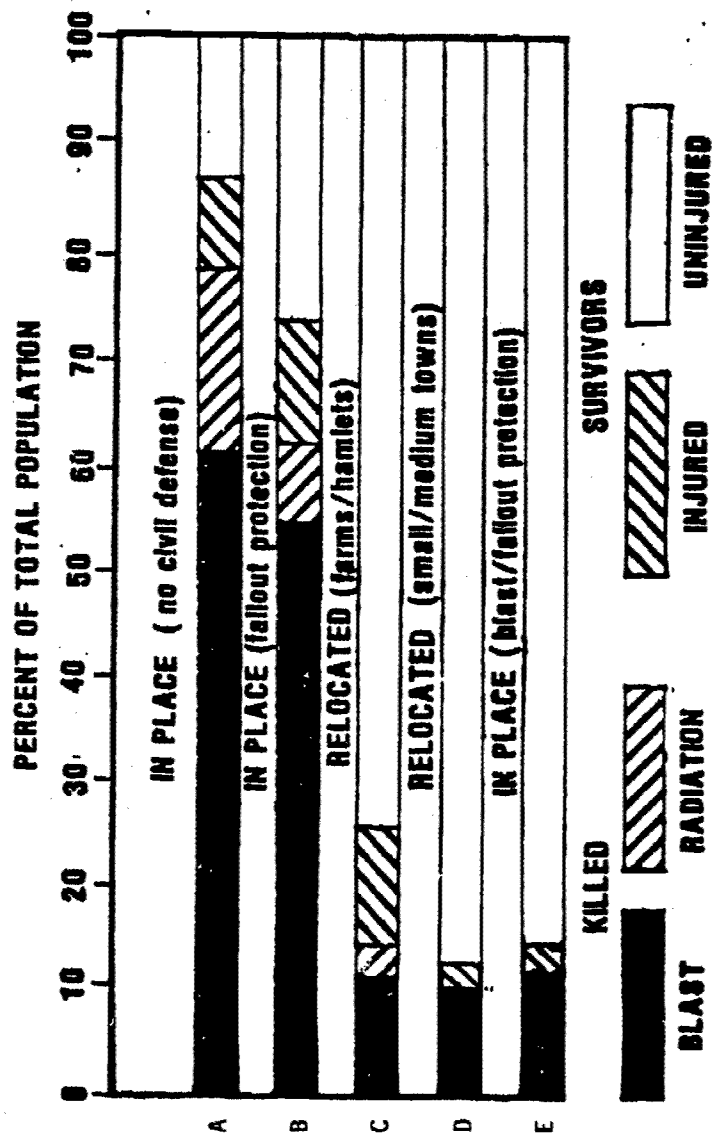
ILLUSTRATIVE DISTRIBUTED COMMUNICATIONS

FIGURE 2



CASUALTY CALCULATIONS FOR ATTACK AGAINST IN-PLACE POPULATION

FIGURE 3



hamlets, performs significantly better than the cheap in-place systems but subjects a significant fraction to injury if no fallout protection is provided due to the very large unit areas at hazard at the lower (but still dangerous) fallout levels. Systems D and E both provide a balanced dispersion considering hardness and the overall dispersion area and both provide good protection but system E is much more expensive than system D because high blast and fallout resistance is required (cost may be on the order of 100X that of system D).

However, another consideration is the reliability of the system--how well can it be trusted to work--especially since it will likely never be tested as a complete system (though perhaps in parts) prior to the need to actually employ it? In-place systems such as system E, if they are physically maintained with ready stocks, have few assumptions regarding their efficiency. They are "in-place" so no extensive relocation is necessary. Only a short warning time is required and no extensive evacuation plans need be put into action, so its false alarm tolerance is high. The major elements of doubt are the extension of timely warning to the individual citizen and long term effects, which can really not be dealt with by any emergency protection system.

On the other hand, system D, which if it works performs as well as the much more costly in-place system E, has many problems. Will the citizens be able to evacuate and set up the system within the available warning time (the nominal design requires a 1-2 week "surge period" to get the population or other resources into a protected status)? How well will stocking, emergency services, and the fabric of local, State, and national organizations tolerate the relocation? What risks are there if CBR protection is set aside? Can the expedient shelters and stocks really be prepared within the surge period or warning time available to the performance levels expected?

The major point is illustrated in Figure 4: for similar performance, freedom from assumptions costs money. The expensive system will be highly reliable, but its cost may not be assessed as equitable to the estimated risk of nuclear war. The inexpensive system may meet current estimates of "a reasonable amount to spend" but important doubts about its ability to work will remain.

One potential solution is to design a framework system which will provide all of the essential functions except those peculiar to the expensive requirements of shelters and stocking and to meet these functions in a design providing common support for peacetime emergencies and the threat of nuclear war. This concept implies that there exists commonality between civil defense and national (peacetime) emergency preparedness functions and, further, that the exercise of the system in meeting general national emergency requirements will of itself prove the performance of the system in meeting a nuclear attack.

There is a basic credibility problem with low cost, framework systems which affects the degree to which the many assumptions (ref. Fig. 4) associated with such systems may be accepted as valid. This is the problem of motivating the actions and effective interest of people oriented systems (which these low-cost framework systems must be) in an environment which sees a serious threat a long way ahead in the future. The concept of an "event horizon" may illustrate the problem (ref. Fig. 5). As the possible time of the

FIGURE 4

FOR SIMILAR PERFORMANCE FREEDOM FROM ASSUMPTIONS COSTS MONEY

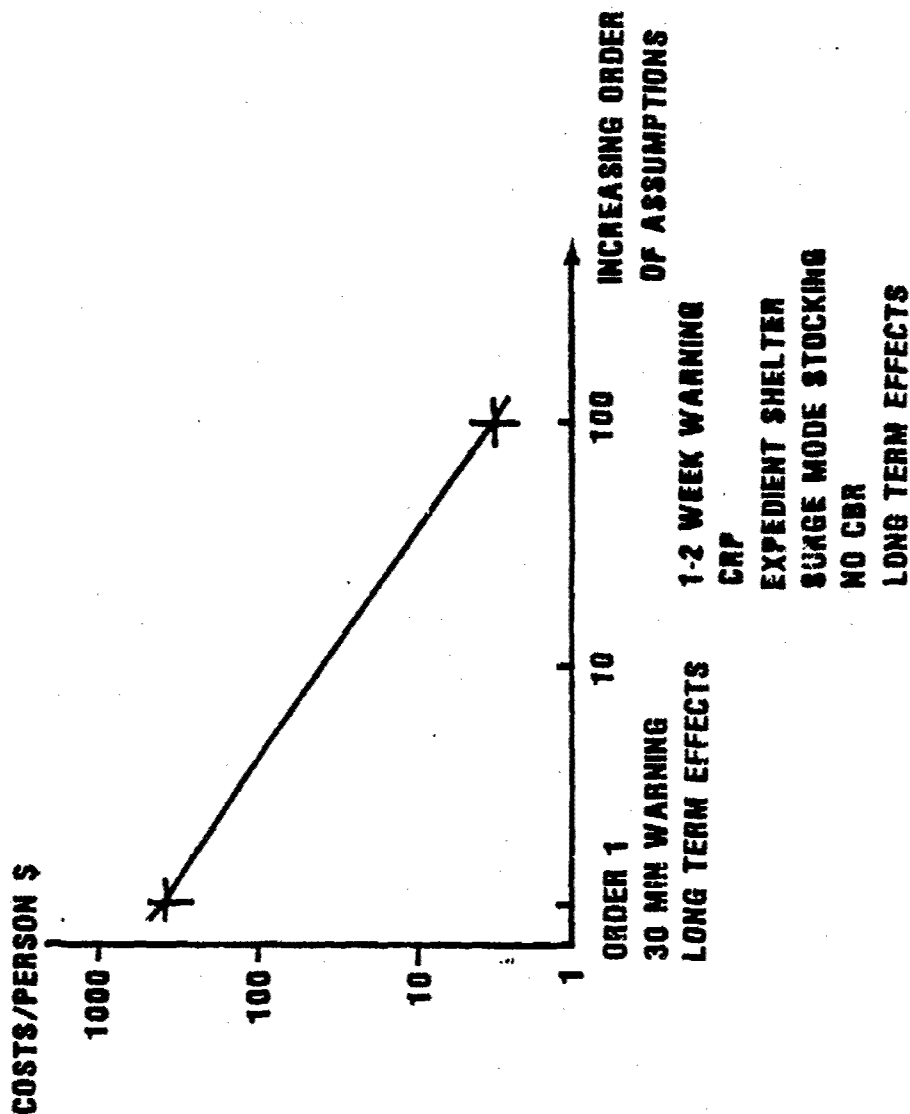
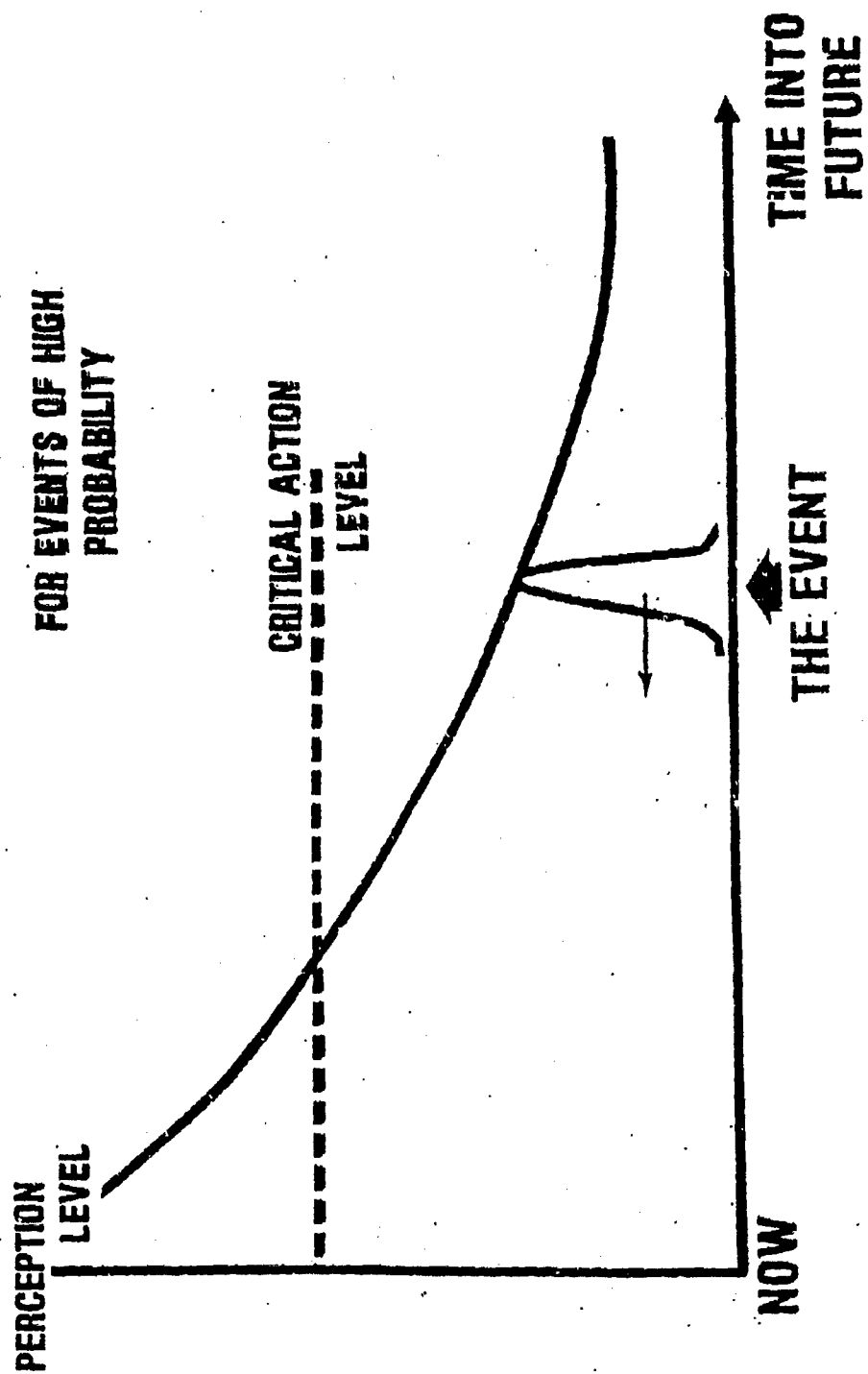


FIGURE 5

THE EVENT HORIZON



occurrence of an event draws toward the present from some future potential occurrence, our perception level of its effects rises. There is some postulated critical level, above which people are strongly motivated to take action. Below this level, the possibility of the event happening is still recognized, but the motivation to take effective action to counter the event drops rapidly. Studies have indicated that for typical critical events (prediction of time of death due to disease, for example) the time interval from the present to that estimated for the event below which the "critical action level" is exceeded is about 2-3 years. If this holds true for civil defense (i.e., the critical effects of nuclear attack) it appears that for any long-term development of capabilities, strong continuing public resolve in the current bipolar world atmosphere may be best sustained through a recognized relevance of such system capabilities to peacetime disasters (i.e., events with a short time perception interval). A design corollary of this effect may be that civil defense systems which rely strongly on "people system" and public acceptance (i.e., the inexpensive systems) may require a strong built-in applicability to "regularly occurring" peacetime emergencies in order to provide an acceptable confidence level in their performance.

PEACETIME UTILITY

The foregoing arguments imply that the distributed survival system has peacetime utility. It can be argued, with some merit, that since there is really no way to test the performance of such systems for nuclear attack alone, the best indicators of performance will be those which can be observed through the action of the civil preparedness system in meeting peacetime emergencies and disasters. It can also be argued that the best design for a distributed adaptive civil preparedness system for nuclear attack is that which is adapted to the problems of peacetime emergencies as well. Some of these arguments are given briefly below:

1. Autonomous local action is required during the first 48 hours of most peacetime disasters.
2. Normal means of communications are often out of order (flood, earthquake, etc.) and the local presence of a distributed adaptive system permits rapid restoration of communications and control.
3. Normal emergency centers are often out of commission--temporary and expedient facilities must be assembled.
4. An accurate and intimate inventory of local resources and an efficient damage assessment and resource allocation scheme is essential.
5. Evacuation activities (for hurricanes, major fires, potential earthquake or flood threats to dams, etc.) are often required and provide a high tension period test of the relocation flow system.
6. Operation of the State/local organizational infrastructure, the heart of the preparedness system, is tested in the exercise of decision and control functions, under periods of high stress.

7. Local economic, financial, vital statistic records and data may be destroyed. The adequacy of recovery measures can be tested and evaluated.

8. Techniques for relief, recovery, and control of ancillary derivative threats (epidemic, fire attendant to physical destruction, loss of transportation, food supplies, etc.) can be exercised and tested to some degree. (The need for local or regional autonomy is less in the peacetime disaster area since, in time, the resources of the major unaffected portion of the country can be applied.)

In summary, the development of distributed survival systems, with strong adaptive properties, can both provide reliable and predictable survivability and recovery potential in the event of actual nuclear attack, and also provide a sound basis for a useful and efficient national emergency preparedness system.

APPENDIX E

BLAST/FIRE INTERACTIONS AFTER
NUCLEAR EXPLOSIONS: A CONTINUUM APPROACH

H. M. Cekirge, Purdue University, School of
Engineering and Technology, 1201 East 38th Street,
Indianapolis, Indiana 46205
Presently, Director of Research
Basic Technology Incorporated

I. S. Tuba, President
Basic Technology Incorporated
7125 Saltsburg Road
Pittsburgh, Pennsylvania 15235

Abstract: In what follows, some basic concepts related to blast/fire interactions after nuclear explosions are presented. Several possible formulations and methods of suggested solutions are discussed. It is clear that further research of the problem area is required and also that the outlined research program could significantly advance the state of knowledge of the subject. The significance of the topic toward overall civil preparedness is enormous.

I. Introduction

After a nuclear explosion, several events typically happen in the following order, Figure 1:

1. There is propagation of a primary fire front;
2. The primary fire front is extinguished by the blast wave;
3. The blast wave damages structures and creates a field of debris; and
4. Secondary fire fronts propagate from arbitrary starting points.

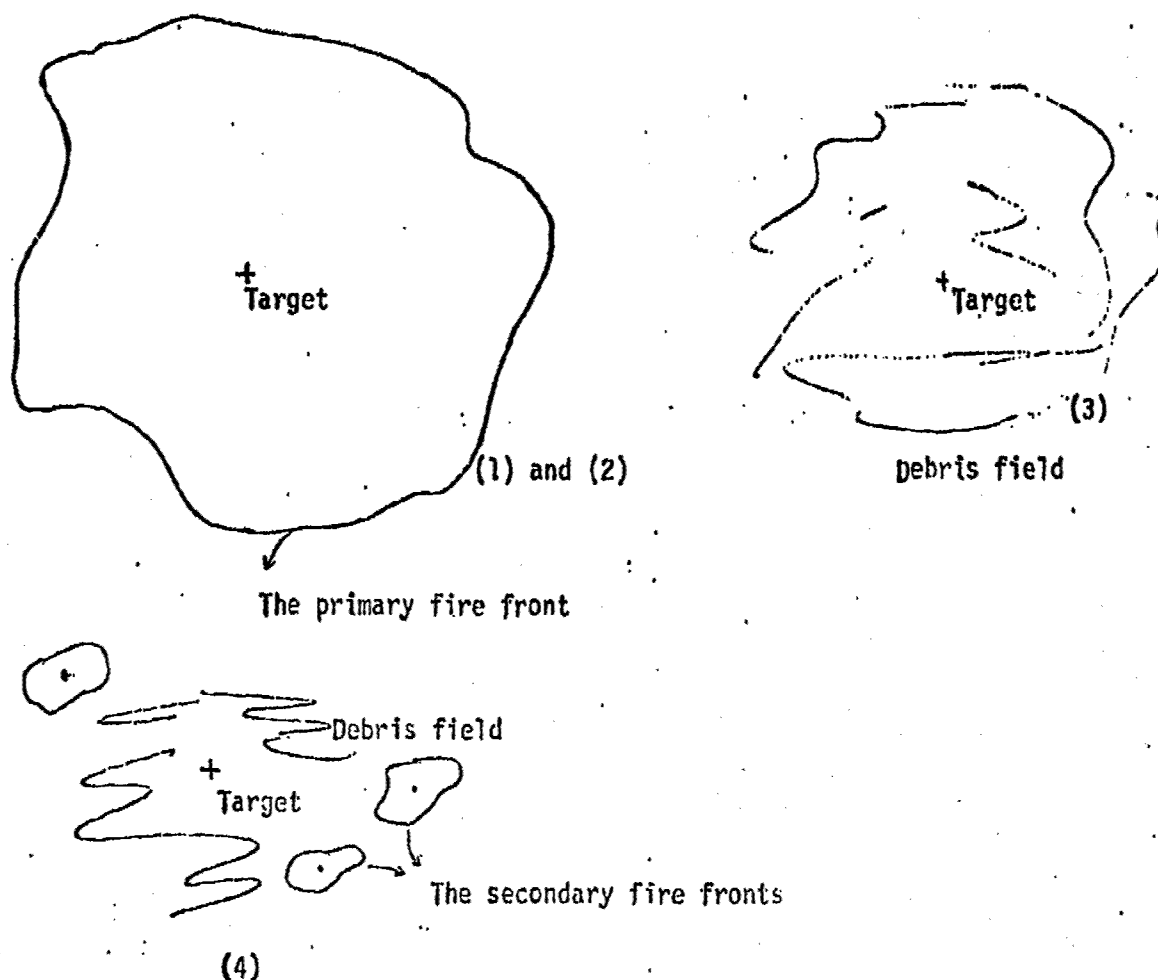


Figure 1. Propagation of fire fronts due to the nuclear explosions.

II. Propagation of Fire Fronts in a Continuum

The primary and secondary fire fronts propagate in undamaged and damaged (debris) urban areas, respectively. Both can be treated as a continuum.

A continuum can be defined by a set of coefficients ξ :

$$\xi^* = \xi \pm \Delta\xi.$$

If $\Delta\xi \approx 0$, the continuum is a deterministic field.

If $\Delta\xi \neq 0$, the continuum is a stochastic field.

In considering fire propagation, urban areas and debris fields are examples of stochastic continua, since the physical parameters of the fire must be defined with a variance $\Delta\xi$. These parameters are the fuel density, the ignition temperature, etc. If otherwise the parameters in a field are essentially constant, it is a deterministic continuum.

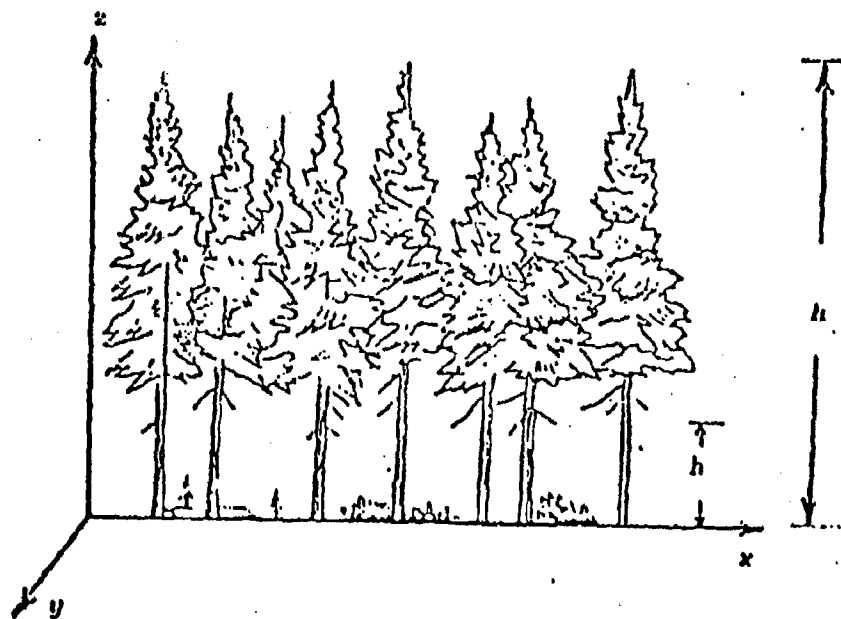


Figure 2. The fuel bed in a forest medium.

III. Fire Propagation in a Deterministic Continuum, (for example, a forest field).

1. Preliminary Remarks

Vegetation fields in forests show more regularity than one might expect; hence, forest media can be considered as a deterministic continua with regard to fire propagation, Figures 2 and 3.



Figure 3. The fuel bed in an urban area.

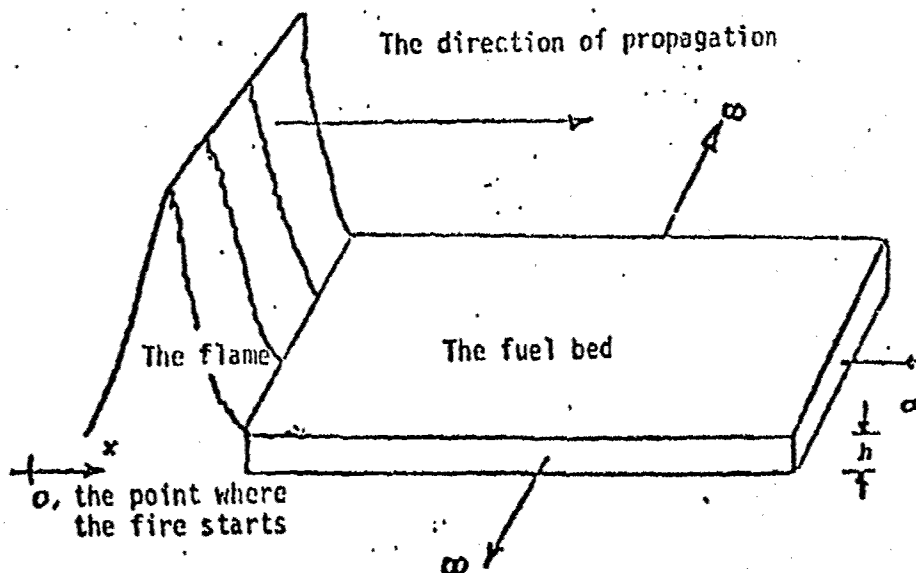


Figure 4. The idealized fuel bed.

There have been a number of studies in an attempt to model the behaviour of fire fronts in forest media. A brief discussion of these mathematical models can be found in Albini [1]. These mathematical models were designed by empirical, statistical and theoretical methods or a combination of these methods. They consider one-dimensional and steady propagation of flame fronts in forests. In these models, the constant propagation speed S is generally found by the relation

$$S = (\sum_{k=1}^K q_k) / \rho h q_y \quad (1.1)$$

where q_k , K , ρ , h , and q_y are, respectively: the amount of heat which comes to or leaves a unit width of fuel bed in unit time due to the k^{th} heat transfer mechanism; the number of heat transfer mechanisms; the specific weight of the fuel; the height of the fuel; and, the necessary heat to ignite the unit weight of the fuel. The evaluation of q_k 's is the main concern in the existing models.

The model presented in this paper considers the propagation of a fire front in forests as a moving boundary value problem while accounting for unsteady fire front velocities. This is the essential contribution of the presented model with respect to the existing models. Convective and radiative heat transfer mechanisms are investigated, and their effects on the behaviour of flame fronts are studied. The one-dimensional propagations of flame fronts, i.e. both translational and radial propagation, are considered in the analysis. Radial propagation of a fire front

is not studied in any of the previous models. These translational and radial propagations are the dominant cases of actual forest fires. Ground and crown fires are studied by adjusting the appropriate forest parameters instead of designing separate models.

A computer package, FIRECON, is developed by using the analysis presented in this paper. Numerical results obtained by FIRECON are presented and compared with experimental results. The prediction sensitivity of the model is also discussed.

2. Analysis

Fire fronts start to propagate and then they translate along one dimension under the influence of wind and topography.

For the unsteady behaviour of the flame front, the average temperature T_{av} in front of the flame front can be written as

$$T_{av}(x, t) = \frac{1}{h} \int_0^h \rho_1(s) T(x, s, t) ds, \quad (2.1)$$

where h , ρ_1 , T , x , s and t are, respectively: the height of the fuel bed; a weight function which describes the fuel bed with respect to the character of the fire, which itself can be either ground or crown; the temperature which is also function of a variable along the height of the fuel bed; a dimension in the direction of the fire movement; a dummy variable; and, time.

Assumptions made for the one-dimensional flame front propagation are stated below, see Figures 4 and 5.

1. The fuel bed is infinitely long in the x direction.
2. The width of the flame front normal to the x direction is infinite.
3. The fuel bed has a constant height.

4. The flame front is a straightline and starts to propagate from the origin.
5. Heat conduction is neglected as a heat transfer mechanism due to the structure and dimension of the problem.
6. The fuel bed ignites when it absorbs a certain amount of heat.

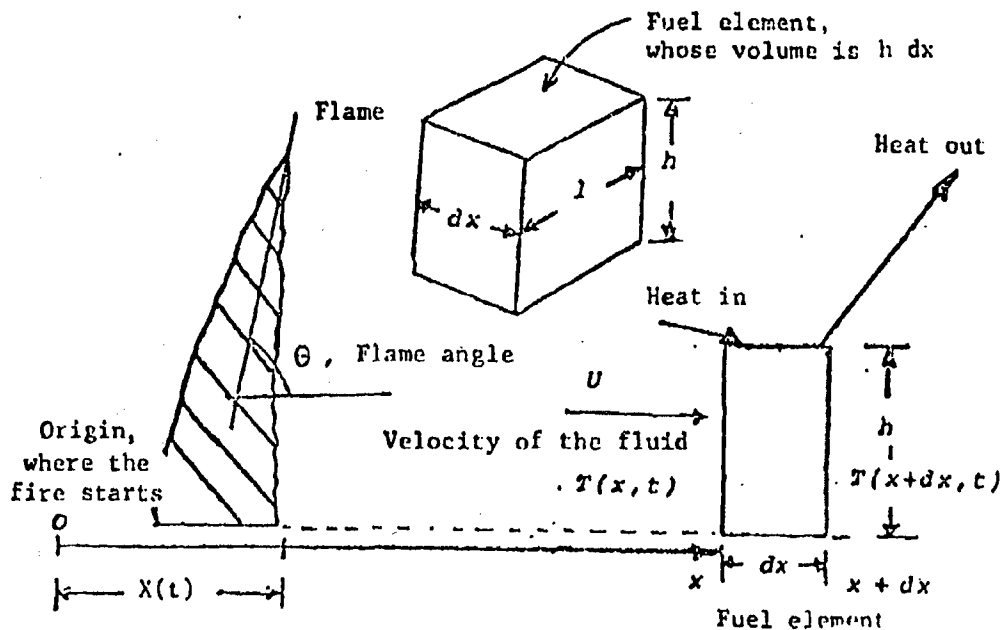


Figure 5. The fuel element considered for the investigation of conservation of energy.

The conservation of energy, in terms of heat, for a fuel elements of height h , length dx and unit width during the lapse of time dt can be written as

Increase in heat = Heat input - Heat output.

The increase in heat in the fuel element is

$$\rho c \frac{\partial T(x,t)}{\partial t} dx h dt, \quad (2.2)$$

where c is the specific heat of fuel.

The heat inputs into the fuel element are described below:

The heat input by convection is

$$U \rho c T(x,t) h dt \quad (2.3)$$

where U is the velocity of the fluid (air or some other gases) in the fuel bed, which is a porous medium.

The heat radiated from the flame within the fuel element is

$$\sigma \epsilon_a F_t (T_f^4 - [T(x,t)]^4) dx dt \quad (2.4)$$

where σ , ϵ_a , F_t and T_f are, respectively: the Stefan-Boltzmann constant; the emissivity of the flame; the geometrical view factor; and, the flame temperature. The geometrical view factor, Steward [2], is

$$F_t = 0.5 \{ 1 - [(x^* - \cos\theta) / \sqrt{1 - 2x^* \cos\theta + x^{*2}}] \} \quad (2.5)$$

and

$$x^* = [x - X(t)]/L, \quad (2.6)$$

where θ , X and L are, respectively: the flame angle (See Fig. 5); the position of the flame front; and, the length of the flame.

The change of F_t during dt is ignored, since this variation has a second order effect on the equation of conservation of energy.

The heat input from the burning embers is

$$\sigma \epsilon_k T_k^4 e^{-a[x-X(t)]} h dt, \quad (2.7)$$

where ϵ_k , T_k and a are: the emissivity of the embers; the ember temperature; and, a coefficient. The radiation from the burning embers occurs throughout the fuel bed.

The heat outputs from the fuel element are described below.

The heat carried from the fuel element by the fluid is

$$U \rho c T(x+dx, t) h dt. \quad (2.8)$$

The fluid velocity in the fuel element is assumed to be constant.

The amount of heat which comes from the burning embers and leaves the fuel element is

$$\sigma \epsilon_k T_k^4 e^{-a[x-X(t)+dx]} h dt. \quad (2.9)$$

The heat loss from the upper surface of the fuel element is

$$\eta [T(x, t) - T_h] dx dt, \quad (2.10)$$

where η is the coefficient for heat losses due to radiation and convection from the upper surface of the fuel element. T_h is the temperature of surrounding air.

For simplicity, it is assumed that the heat loss for drying the fuel is considered as part of the heat for the ignition of the fuel. This effect is treated as part of the boundary conditions of the problem.

Expressions (2.2), (2.3), (2.4), (2.7), (2.8), (2.9) and (2.10) together yield the equation of conservation of energy as

$$\frac{\partial T}{\partial t} + U \frac{\partial T}{\partial x} = G[x, X(t), T], \quad (2.11)$$

where

$$\begin{aligned} G[x, X(t), T] = & \alpha_1 [x-X(t)] T^4 + \alpha_2 T + \alpha_3 [x-X(t)] \\ & + \alpha_4 [x-X(t)] T_f^4 + \alpha_5 \end{aligned} \quad (2.12)$$

and

$$\begin{aligned}\alpha_1 &= -(\sigma c_a / \rho c h) F_t [x - X(t)] , \\ \alpha_2 &= -\eta / \rho c h , \\ \alpha_3 &= (\sigma c_k a T_k^4 / \rho c) e^{-a[x - X(t)]} , \\ \alpha_4 &= (\sigma \epsilon_a T_f^4 / \rho c h) F_t [x - X(t)] , \\ \alpha_5 &= (\eta / \rho c h) T_h .\end{aligned}$$

The initial condition of the problem is

$$t = 0 \quad T = T_0(x) \quad (2.13)$$

where $T_0(x)$ is the temperature distribution in the medium prior to the propagation of the fire front. The moving boundary of the problem is the fire front where the fuel burns and becomes ashes and residue. The condition at this boundary is

$$x = X(t) \quad T[X(t), t] = T_y , \quad (2.14)$$

where T_y is the evaluated ignition temperature. The value of T_y can be expressed as

$$T_y = (Q_y + n M) / \rho c , \quad (2.15)$$

where Q_y , n and M are: the heat necessary to ignite a unit weight of fuel; the moisture content in a unit weight of fuel; and, the heat necessary to dry the fuel which has one unit of moisture.

The initial condition for the moving boundary is

$$t = 0^+ \quad x(0^+) = 0^+ . \quad (2.16)$$

The illustration of the moving boundary value is seen in Fig. 6.

One dimensional models are quite adequate in most cases where the fire front is being drifted by wind or topography. However, the initial behaviour of the fire can best be described by its radial propagation. The boundary value problem in this case can

be obtained as in the previous case, and

$$\frac{\partial T}{\partial t} + u_r \frac{\partial T}{\partial r} = H[r, R(t), T] \quad (2.17)$$

where

$$H[r, R(t), T] = \beta_1 [r - R(t)] T^4 + \beta_2 T + \beta_3 [r - R(t)] + \beta_4 [r - R(t)] + \beta_5 \quad (2.18)$$

$$\beta_1 = -(\sigma \epsilon_a / \rho c h) F_r [r - R(t)],$$

$$\beta_2 = -\eta / \rho c h,$$

$$\beta_3 = (\sigma \epsilon_k a T_k^4 / \rho c) e^{-a[r - R(t)]},$$

$$\beta_4 = (\sigma \epsilon_a T_f^4 / \rho c h) F [r - R(t)],$$

$$\beta_5 = (\eta / \rho c h) T_h,$$

and initial and boundary conditions are

$$t = 0 \quad T = T_0(r), \quad (2.19)$$

$$r = R(t) \quad T[R(t), t] = T_y \quad (2.20)$$

and

$$r = 0^+ \quad R(0^+) = 0^+. \quad (2.21)$$

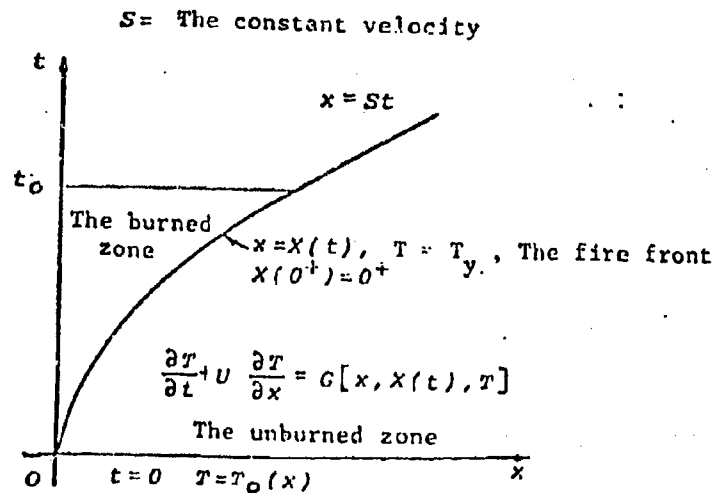
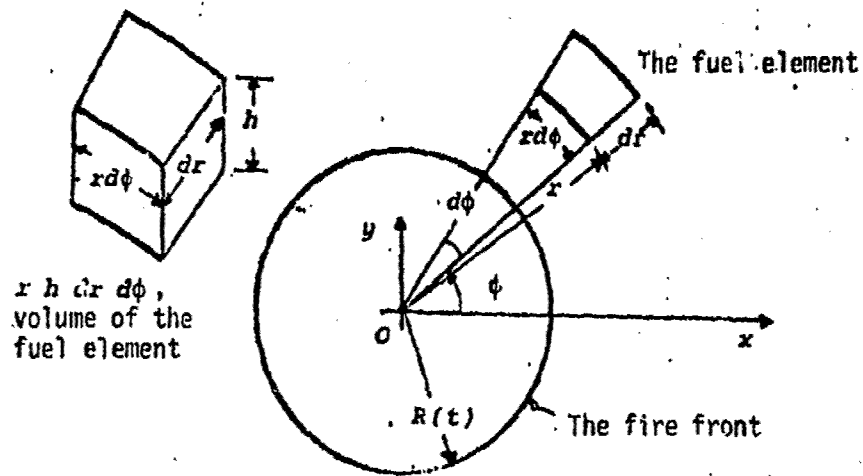
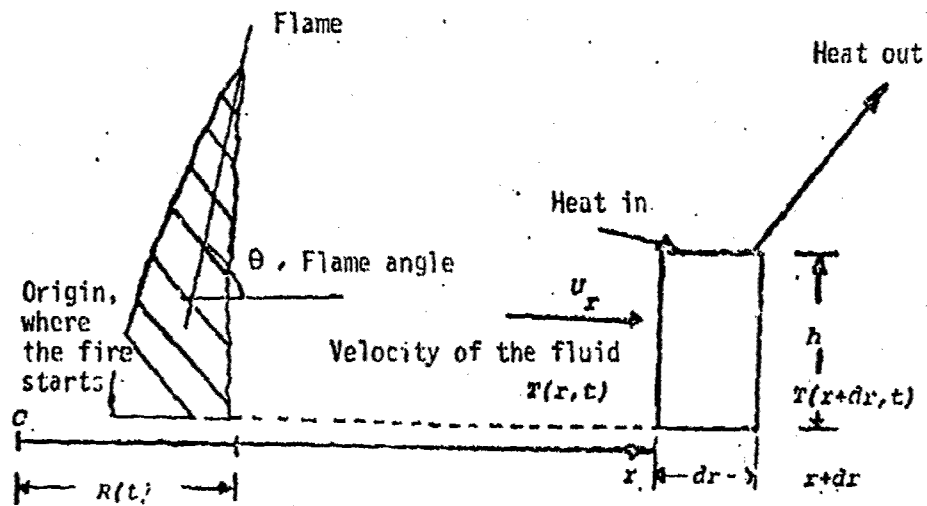


Figure 6. The boundary value problem in the t - x plane.



The radially propagating fire front on the horizontal plane



The section along the angle ϕ

Figure 7. The radially propagating fire front.

In these expressions r , U_r , $R(t)$ and F_r are, respectively: the radial distance; the radial velocity of the fluid in the medium; the trajectory of the fire front; and, the geometrical view factor for the cylindrical fire front, see Figures 7 and 8.

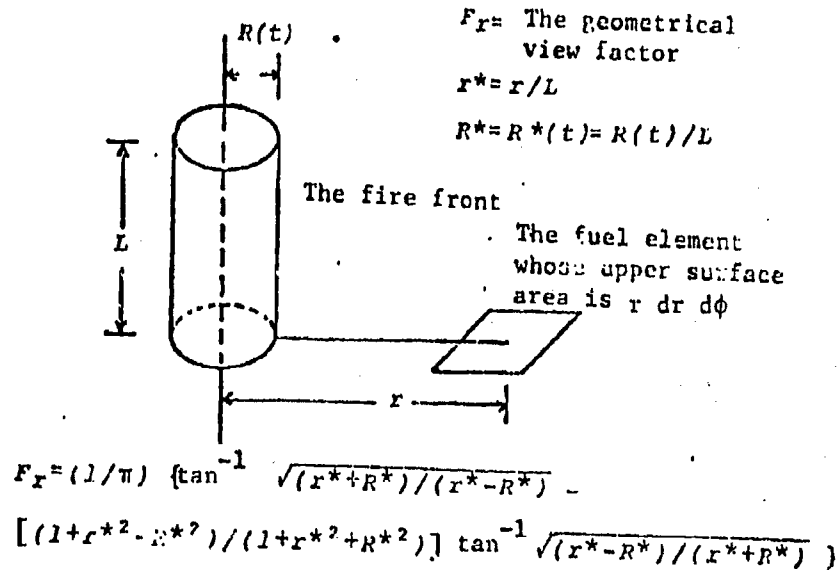


Figure 8. The radially propagating fire front and the fuel element.

It is an observed fact that the velocity of the fire front for both cases of propagation, i.e. translational and radial, reaches a constant value. In this case, the moving boundary value problem is

$$\frac{\partial T}{\partial t} + U \frac{\partial T}{\partial x} = f(x, St, T), \quad (2.22)$$

$$t = t_0 \quad T = T_1(x), \quad (2.23)$$

$$x = S t \quad T(St, t) = T_y, \quad (2.24)$$

and
$$t = t_0 \quad X = X_s \quad (2.25)$$

where x , f , t_0 , T , and X_g respectively: the space coordinate; the F or G function in equation (2.1) or (2.17); the instant at which the fire front reaches a constant speed; the temperature distribution in the field at $t=t_0$; and, the coordinate of the fire front at $t=t_0$.

The moving boundary value problems stated in this section are highly nonlinear due to the structure of the function f . The problem is further complicated because of its moving boundary. For these reasons, the finite difference method, a numerical approach, is chosen for the solution of the problem. The method will be explained in the next section.

3. Solution With the Finite Difference Method

The moving boundary value problem is restated for the translational and radial propagating fire fronts in the following form

$$\frac{\partial T}{\partial t} + U \frac{\partial T}{\partial x} = f [x, X(t), T] \quad (3.1)$$

$$t = 0 \quad T = T_0(x) , \quad (3.2)$$

$$x = X(t) \quad T[X(t), t] = T_y \quad (3.3)$$

$$\text{and} \quad t = 0^+ \quad x = 0^+ \quad (3.4)$$

Equation (3.1), in a discrete form in the grid of Fig. 9, can be written at x_i and t_j when the fire front reaches the point x_j as

$$\frac{T_{i,j} - T_{i,j-1}}{\Delta t_j} + U_i \frac{T_{i,j} - T_{i-1,j}}{\Delta x} = f(x_i, X_j, T_{i,j}^*) \quad (3.5)$$

which is consistent with equation (3.1), McCracken et al. [3], also noting that

$$x_i = (i-1)\Delta x \quad i = 1, 2, \dots, \infty , \quad (3.6)$$

$$t_j = \sum_{k=1}^j \Delta t_k , \quad \Delta t_1 = 0 , \quad k = 1, 2, \dots, \infty , \quad (3.7)$$

$$x_j = (j-1) \Delta x \quad j = 1, 2, \dots, \infty \quad (3.8)$$

$$\text{and} \quad T_{i,j}^* = (T_{i,j-1} + T_{i-1,j})/2. \quad (3.9)$$

In these relations, i , j , and k are indices and Δx , Δt_j , T_{i0} and U_i are respectively: the difference in x ; the time difference when the fire front propagates between x_{j-1} and x_j ; the temperature at the points $x_i > x_j$; and, the velocity of the fluid at x_i . Equation (3.5) gives the values of $T_{i,j}$ as

$$T_{i,j} = [\Delta t_j \Delta x f(x_i, x_j, T_{i,j}^* + \Delta x T_{i,j-1} + U_i \Delta t_j T_{i-1,j})] / (\Delta x + \Delta t_j U_i) \quad (3.10)$$

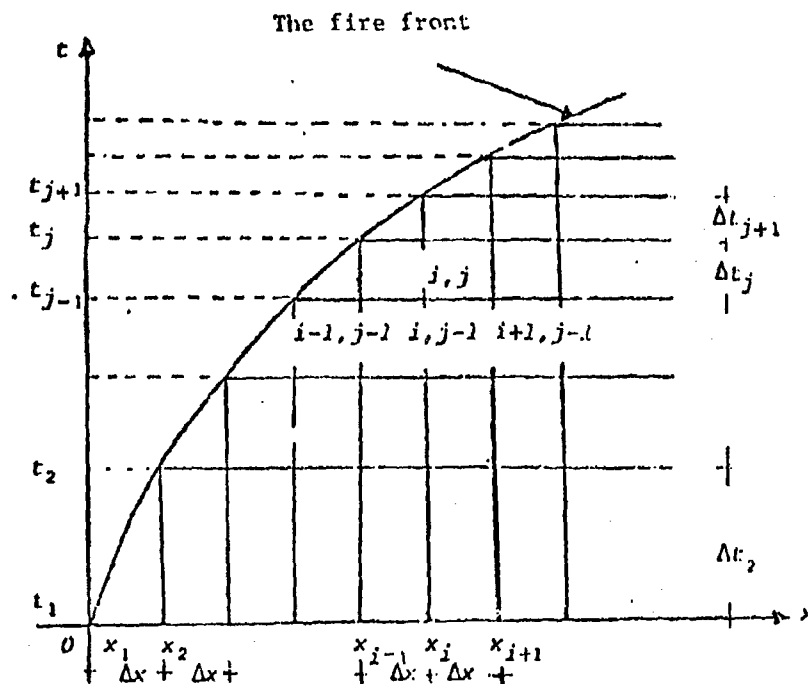


Figure 9. The grid constructed in the t - x plane for the solution of boundary value problem.

The discrete forms of the initial and boundary conditions

are

$$T_{1,1} = T_0(x_1) \quad (3.11)$$

and

$$T_{j,j} = T_{j-1,j} = T_y \quad (3.12)$$

By considering

$$T_{j,j}^* = (T_y + T_{j,j-1})/2, \quad (3.13)$$

equations (3.10), (3.11) and (3.13) yield that

$$\Delta t_j = (T_j - T_{j,j-1}) / f(x_j, x_{j-1}, T_{j,j}^*). \quad (3.14)$$

Equations (3.14), (3.7) and 3.8) define the position of the fire front; also, the temperature field at the instant t_j and at the point x_1 ($x_1 > x_j$) can be found by equation (3.10). This is the solution to the moving boundary value problem.

The ratio

$$S_1 = \Delta x / \Delta t_{1+1} \quad (3.15)$$

gives the velocity at x_1 . The criterion

$$|\mu| = |(S_{1+1} - S_1) / S_1| < \mu_0 (< 1) \quad (3.16)$$

defines the point x_s at which the flame front reaches its constant value. Then, the trajectory of the flame front can be defined as

$$t = (x - x_s) / S + t_s \quad (3.17)$$

where t_s is the time from the start of the fire to the time at which the fire front reaches a constant value.

The convergence of the numerical scheme is investigated by considering several values of Δx . If the final grid in the t - x plane is constructed by choosing a value of Δx , then for any value of Δx smaller, convergence is obtained if the arrival time of the fire front to the maximum observation distance differs by a negligible

amount for the two values of Δx .

The choice of Δt_j , through equation (3.14), provides stability to the numerical scheme. This choice assures that any value of temperature in front of the fire front can not exceed T_y which is the maximum temperature in the medium.

4. Applications and Conclusion

A computer package, FIRECON, Cekirge [4], has been prepared based on the analysis presented in the previous section. The accuracy of the theoretical prediction, using FIRECON, is tested by comparing it with the experimental data given by Wooliscroft [5], [6] and [7], and also by Telisin [8]. This comparison is shown Table 1. In this table, s_1^* , and s_2^* are the constant velocities of the front found experimentally and obtained in [8] which considers only radiation. s_3^* and s_4^* are the velocities of the fire front, evaluated by FIRECON, when it reaches a constant value, considering only radiation and radiation and convection effects, respectively. The results are compared in the sense of ϕ_c which is

$$\phi_c = \left[\sum_{p=1}^{p_0} \omega_p^2 / p_0 \right]^{1/2} \quad (4.7)$$

where ω_p , p and p_0 are respectively: the relative error in the p^{th} evaluation; an index; and, the numbers of forest fires considered.

The following conclusions can be made by examining Table 1:

1. The evaluations which consider only radiation effects, i.e. s_2^* and s_3^* , show almost the same sensitivity, $\phi_c = 0.73$ and 0.71 respectively.
2. The evaluations which consider both radiation and convection effects, i.e. s_4^* values, improve the prediction sensitivity for the propagation of fire fronts in forests since ϕ_c

Table 1. COMPARISON OF EXPERIMENTAL AND THEORETICAL RESULTS

Forest Fire No.	S_1^* m/s	S_2^* m/s	$\omega_p = \frac{S_1^* - S_2^*}{S_2^*}$	$S_3^*, \alpha_k = 0,$ m/s	$\omega_p = \frac{S_1^* - S_3^*}{S_3^*}$	$S_4^*, \alpha_k = 0,$ m/s	$\omega_p = \frac{S_1^* - S_4^*}{S_4^*}$
1	0.013	0.015	-0.13	0.014	-0.07	0.014	-0.07
2	0.086	0.069	0.25	0.040	1.15	0.084	0.02
3	0.300	0.132	1.27	0.209	0.44	0.298	0.01
4	0.015	0.013	0.15	0.009	0.66	0.009	0.66
5	0.088	0.104	-0.15	0.146	-0.40	0.146	-0.40
6	0.210	0.125	0.58	0.161	0.30	0.202	0.04
7	0.028	0.071	-0.61	0.048	-0.42	0.048	-0.42
8	0.150	0.234	-0.47	0.224	-0.33	0.224	-0.33
9	0.146	0.600	1.43	0.060	1.43	0.144	0.01
ϕ_c			0.73		0.71		0.31

becomes 0.31 for the case. Convection has been included by choosing an imaginary flow in the forest by considering the existing wind in the medium. The choice of the proper values for U (the fluid velocity) is made by the relation

$$U = \alpha U_w, \quad 0 < \alpha < 1 \quad (4.2)$$

where α and U_w are respectively: a coefficient; and the wind velocity. The selection of values for α was based on the computer experiments, but with no aid from experimental evidence, since the references [5], [6] and [7] give only values of wind and do not provide any information about the flow inside the forest. For the selection of α 's, it is assumed that the flow velocity in the forest is less than the measured wind velocity.

Moreover, the computed results given by FIRECON show that fire fronts propagate radially faster than they translate. This fact can also be seen by considering the structure of the geometrical view factor, which is the energy scattering property of the fire front in radially propagating forest fires.

The consideration of energy losses also improves the sensitivity of prediction of FIRECON. However, results of this are not given in this paper, since the choice of heat loss coefficients could not be based on experimental facts.

The contribution of this study can be summarized as:

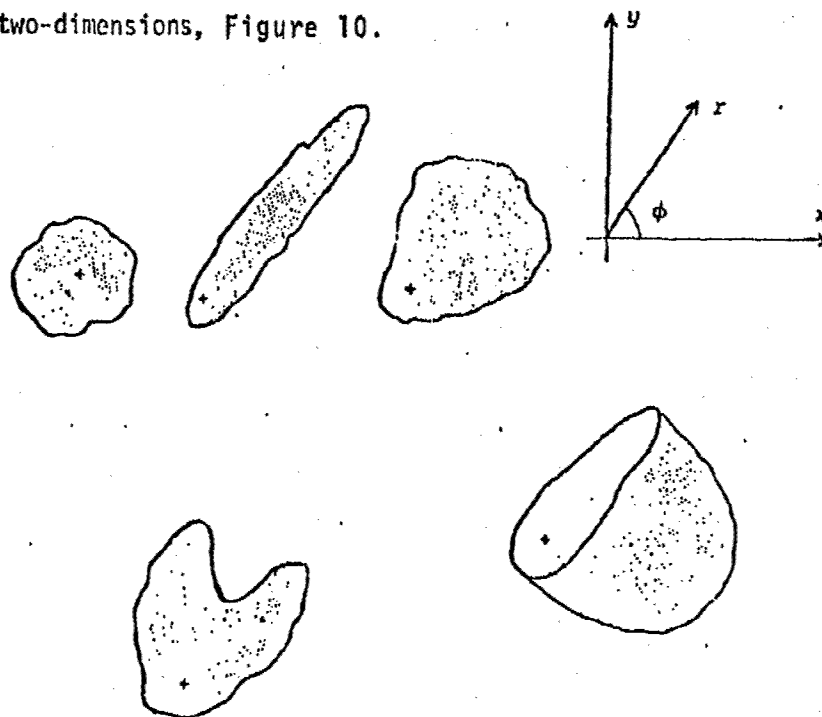
1. The mathematical model and the computer package, FIRECON, provide possibility of predicting unsteady as well as the radial behaviour of fire fronts.
2. The effects of convection and heat losses can be included in the prediction.

3. The temperature field in front of the fire front can also be evaluated. This would provide valuable information when considering the use of fire extinction methods such as trenching, water or chemical spraying, etc..

It should also be mentioned that the calibration and improvement of the model needs an enormous amount of detailed experimental data. It is obvious, of course, that it would be expensive, lengthy and difficult to obtain such data. However, the importance of the problem justifies efforts toward acquiring this data.

5. Propagation of Fire Fronts in Two-dimensions

The problem must be studied as a moving boundary value problem in two-dimensions, Figure 10.



+ The point where the fire starts

Figure 10. Propagation of fire fronts in two-dimensions

6. Stability of the Fire Front; Extinguishment .

On page 15, equation (3.14)

$$\Delta t_j = (T_y - T_{j,j-1}) / f(x_j, x_{j-1}, T_{j,j}^*)$$

gives the incremental movement of the fire front. The function

f depends upon all of the physical parameters of the fuel bed

including the velocity of the fluid (air and other gases) in the

medium. The condition

$$\Delta t_j > \Delta t$$

is the satisfactory condition for the slowing or stopping of the

fire front, which corresponds to its extinguishment and Δt is an

experimental value. When Δt_j reaches the value Δt , the gases and the flame, which cause the kindling, are removed by the air flow through the medium.

7. Thoughts on Improvement of the Model

The model must be compared with more experimental data, to better

define the α 's which represent the heat losses in the fuel bed.

The turbulent convection energy transfer can also be considered

$$a_1 (T_{fl} - T_y) \exp(-a_2 x^2)$$

where T_{fl} = the flame temperature

and a_1 and a_2 = the coefficients.

The coefficients a_1 and a_2 must be determined.

IV. Flow Field in the Medium

The excited shock wave due to the nuclear explosion is the main reason for the convective energy transfer. The shock propagates in the medium until it attenuates to zero strength.

The propagation of the shock wave effects the energy equation, i.e. the temperature and flow fields are coupled in the medium.

Then the field equations for both fields,

$$L_1 (T, U) = 0$$

$$\text{and } L_2 (T, U) = 0.$$

L_1 = the differential operator for the energy field.

L_2 = the differential operator for the flow field.

In section III, L_2 is ignored since the flow is assumed to be excited by wind alone, and is also assumed to be known apriori.

However, the blast/fire interaction can be treated as a decoupled system.

Furthermore, a porosity concept of the flow field in an urban area

must be considered. Obviously, this concept is strongly dependent upon the concentration of buildings in the urban area.

V. Fire Propagation in a Stochastic Medium

The fire parameters must be determined from maps which depict the target area. For the propagation of the primary fire front, the area maps can be easily analyzed to determine the fire parameters. However, the parameters of secondary fires show a strong probabilistic nature due to the structural damage from the blast wave.

The source points for the secondary fires can be determined in a probabilistic manner by reconsidering the extinguished fire front and the fire field in a medium which does not have a shock wave but which does have a new flow field. The values of Δt_j 's become smaller than the critical Δt and then the fire starts. For either primary or secondary fires, the problem should be handled as a two-dimensional moving boundary value problem in a stochastic medium. The coupling and decoupling of the temperature

and the flow field are the main difficulties in definition of the problem.

In stochastic models, the coefficients and parameters are defined with a variance, i.e.,

$$C + \Delta C$$

and the results also exhibit a variance such as the position of the fire front

$$R(t) \pm \Delta R(t)$$

and the temperature field

$$T \pm \Delta T.$$

These models give more reliable results.

The jumping embers and burning materials (spotting) is also an important mechanism for the transfer of fire. The spottings occur in a probabilistic manner, and these burning materials become starting points of new fires.

VI. Research Objectives

1. Design an algorithm to find the parameters for primary fires from a given map of an undamaged area. (Perhaps, a new computer hardware is necessary to design for offensive and defensive purposes.)

2. Design an algorithm to find the parameters for secondary fire fronts, provided the structural damage and its consequences can be determined.
3. The deterministic mathematical models must be studied and solved.
4. The stochastic mathematical models must be prepared and solved.
5. The optimum algorithms and computer packages must be prepared.
6. Model studies must be done.

VII. Final Remarks

The one-dimensional deterministic model is a limited attempt for the problem, which covers maybe ten percent of the phenomenon.

This article will also be published partially in the Journal of "Computers and Mathematics and its Applications."

REFERENCES

1. Albini, F.A., Estimating Wildfire Behaviour and Effects, USDA Forest Ser., Gen. Techn. Rep. INT-30, 1976.
2. Steward, F.R., Radiative Heat Transfer Associated with Fire Problem, Heat Transfer in Fires: Thermophysics, Social Aspects, Economic Impact, (edit.) Blackshear, P.L., Scripta Book Com., Washington, D.C., John Wiley, 1974.
3. McCracken, D.D., Luther, H.A. and Wilkes, J.O., Applied Numerical Methods, John Wiley, New York, 1965.
4. Cekirge, H.M., Dozentship Thesis, Bogazici University, Sept. 1977.
5. Wooliscroft, M.J., A Report on Forest Fire Fieldwork (New Forest, Mar. 1966), Joint Fire Research Organization, Fire Res. Note No. 693, 1968.
6. Wooliscroft, M.J., Notes on Forest Fire Fieldwork (New Forest, 1967), Joint Fire Res. Org., Fire Res. Note No. 740, 1969.
7. Wooliscroft, M.J., A Report on Forest Fire Fieldwork, (New Forest, Mar. 1968), Joint Fire Res. Org., Fire Res. Note No. 744, 1969.
8. Telisin, H.P., Flame Radiation as a Mechanism of a Fire Spread in Forests, Heat Transfer in Flames, Chap. 29, Washington, D.C., John Wiley, 1974.

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Mr. A. P. Brackebusch
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Northern Forest Fire Laboratory
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Cincinnati, Ohio 45211

Mr. Frank Agardy
URS Research Company
155 Bovet Road
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Mr. Norman J. Alvares
Lawrence Livermore Laboratory
Box 808, L-Stop 442
Livermore, CA 94550

Mr. Craig C. Chandler
Director, Forest Fire Research
U.S. Forest Service
Department of Agriculture
Washington, D.C. 20250

Dr. Conrad V. Chester
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, Tennessee 37830

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Underwriters Laboratories, Inc.
333 Pfingsten Road
Northbrook, Illinois 60062

Mr. W. L. Huff
USAE Waterways Experiment Station
Post Office Box 631
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#30 White Plains Court
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750 Welch Road
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R1/1038
TRW
One Space Park
Redondo Beach, CA 90178

Mr. Thomas C. Goodale
SRI International
Menlo Park, CA 94025

Mr. H. L. Murphy
H. L. Murphy Associates
Box 177
San Mateo, CA 94401

Mr. Richard Park
National Council of Radiation
Protection & Measurements
7910 Woodmont Avenue
Bethesda, MD 20014

Mr. John Rempel
SRI International
Menlo Park, CA 94025

Mr. Thomas Waterman
IITRI
10 W. 35th Street
Chicago, Illinois 60616

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Defense Intelligence Agency
Attn: CKW DB-4C2
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U.S. Fire Administration
Washington, D.C. 20230

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SRI International
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National Fire Protection Assoc.
470 Atlantic Avenue
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Department of the Aerospace
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University of California
San Diego
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SRI International
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Mr. Leo A. Schmidt
Institute for Defense Analyses
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BLAST/FIRE INTERACTIONS

Program Formulation

DETACHABLE SUMMARY

October 1978

Final Report

**By: Stanley B. Martin
Raymond S. Alger**

Prepared for:

DEFENSE CIVIL PREPAREDNESS AGENCY

Washington, D.C. 20301

Attn: David W. Bensen, COTR

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SUMMARY

Fire from a nuclear-weapon attack is a direct threat to the population of the United States and an indirect, long-term threat to national survival because fire can destroy the shelter, sustaining resources, and industrial machinery essential to economic recovery. Unresolved questions about interactions between blast effects and fire effects preclude any reliable estimates of the incendiary outcome of a nuclear attack on the United States. As such, these uncertainties are a major obstacle to defense planning and interfere with national security policymaking at the highest levels.

To rectify the technical deficiencies underlying the lack of predictability of the incendiary outcome of nuclear attack on the United States and to formulate a well-directed program of research, the Defense Civil Preparedness Agency contracted with SRI International in early 1978 to convene a conference of authorities on fire, air blast, structural response, and related technologies. This report covers the proceedings of that conference and its accomplishments.

The conferees identified the technical deficiencies that prevent or inhibit the development of a theoretical or analytical basis for predicting fire effects under the uncertainties introduced by interaction with air-blast waves and blast effects. Recognizing the inherent uncertainties concerning any future nuclear event, and constrained to a planning philosophy that requires the level of technical understanding to be consistent with practical utility and commensurate with the level of perceived threat, the conferees developed a logical, analytical framework for structuring and performing a research program to either eliminate technical deficiencies or reduce to an acceptable level the contribution these deficiencies add to the uncertainties in damage prediction. Recommendations were made for early attention to specific deficiencies that are readily distinguished as key issues that prevent the development of credible fire/blast models. Beyond this, most program elements could be seen in outline only, although the conferees unanimously held that analytical modeling of blast-fire interactions was not only the goal of the program, but a necessary adjunct, through sensitivity analysis, of program planning and review.

This report describes, in some detail, the first two years (fiscal years 1979 and 1980) of an optimally funded program of 5-yr duration. The technical objective of the program was to produce an analytical method for reliably predicting fire behavior and incendiary-damage production. Three levels of modeling detail were seen as the minimum requirement:

- A general urban fire-distribution/spread model for areas of light-to-moderate building damage.
- A "hole-in-the-doughnut" model, applicable to areas of heavy damage.
- A specific-resource vulnerability model, applicable to a critical resource threatened by fire exposure.

Choice and/or development of the necessary analytical methodology is a first order of business. Unfortunately, little progress can be made until the basic blast/fire interactions are understood. This, in turn, necessitates experimental investigations of the causal factors and concepts, and determinations of input data and empiricisms. Therefore, a strong experimental program is recommended to support and interactively complement the theoretical and analytical developments.

The FY79 program, estimated to cost \$920K, initiates development of blast/fire predictive modeling complemented by analysis of dynamic structural response and debris distribution calculations for single structures and a renewed attempt to estimate secondary fire incidence from retrospective, historical data on earthquakes, wind storms, and explosions. Experimental tasks include drag-lift experiments to complement debris translation calculations and shocktube studies of the physics of interactions of blast waves with burning objects of idealized geometry and composition. These experiments would be coordinated with the development of a dynamic-flow, boundary-layer theory for shock/fire interaction.

The FY1980 program would see a substantially increased level of activity, estimated to cost about \$1.3 million. Much of the work initiated in FY79 would be continued; verification experiments in connection with Misty Castle high-explosive tests are also suggested. Structural responses and debris distribution calculations would attempt to treat the more practical situations found in urban complexes. The development of the predictive blast/fire analytical models would parallel large and small scale experiments. If sensitivity studies, initiated in FY79, show the uncertainties to be important, the doubtful ignition thresholds for large areas of mixed fuels, especially the question of whether transient ignition is or is not important, would be reliably established through experiment.

This program is expected to culminate with one or more full-scale simulations of urban/industrial complexes subjected to the combined blast and fire effects of a nuclear explosion, possibly involving a HE test series dedicated to resolution of blast/fire problems.

A program of this scope, and relatively short duration, requires strong, consistently applied monitoring and coordination to ensure that the obtainable goals are significant, to maintain a level of performance that is consistent with need, and to synchronize complementary or dependent elements. These requirements point to the need for DCPA to

designate a lead laboratory to conduct some key across-the-board elements of the research and to direct and coordinate the variety of complimentary tasks done by contractors and other contributors.